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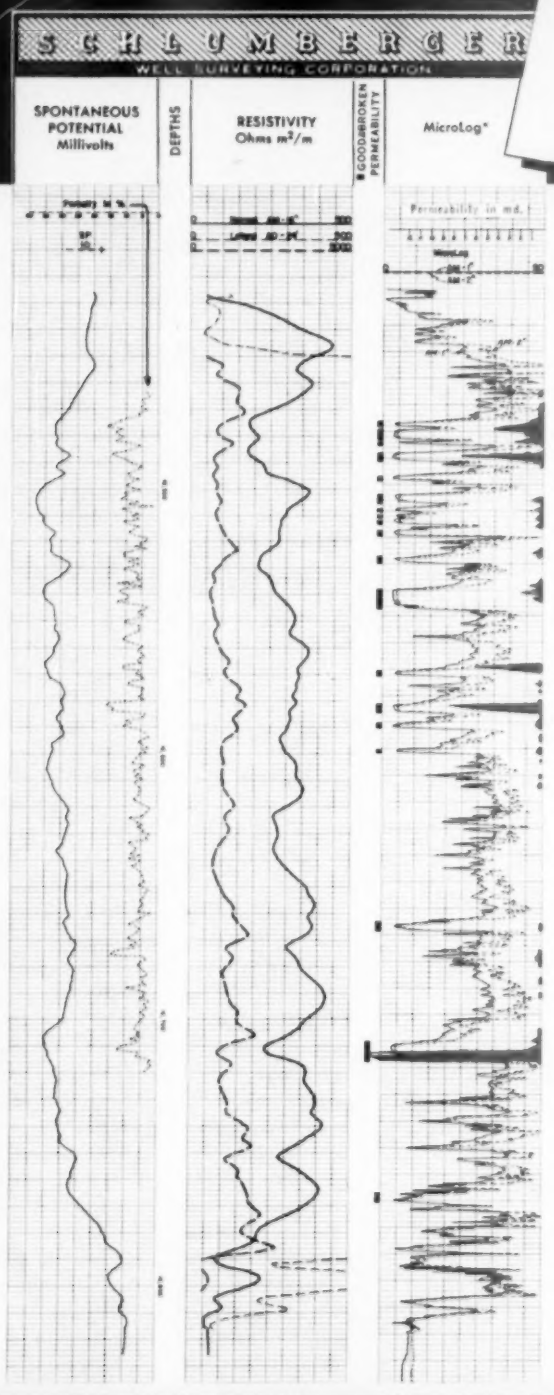

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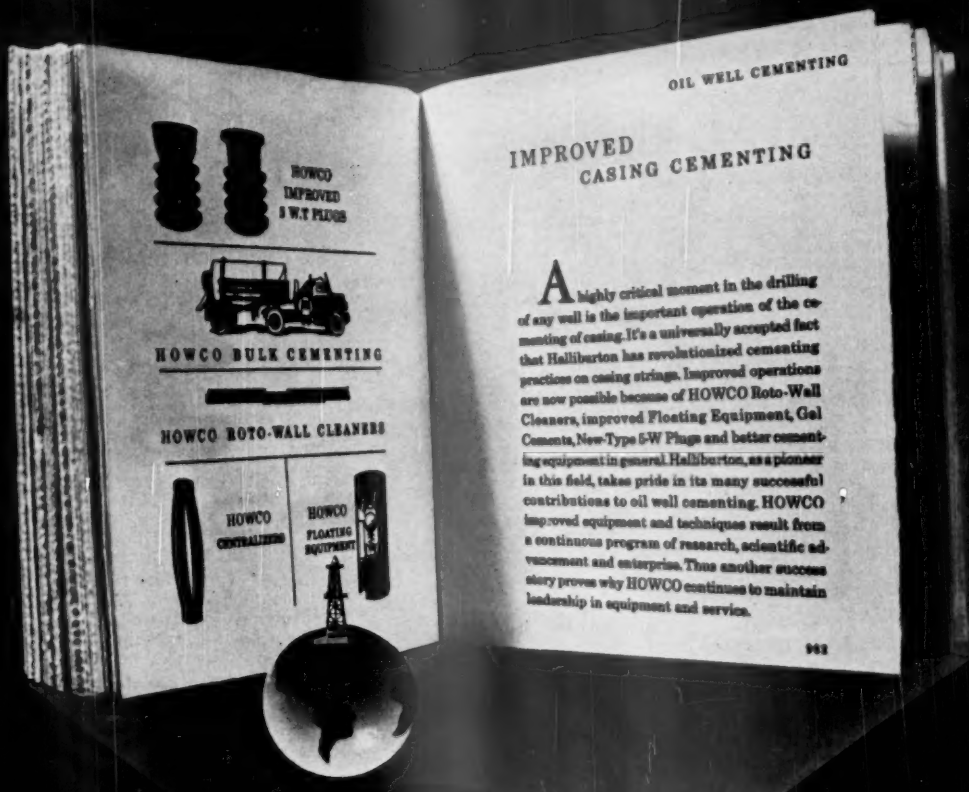
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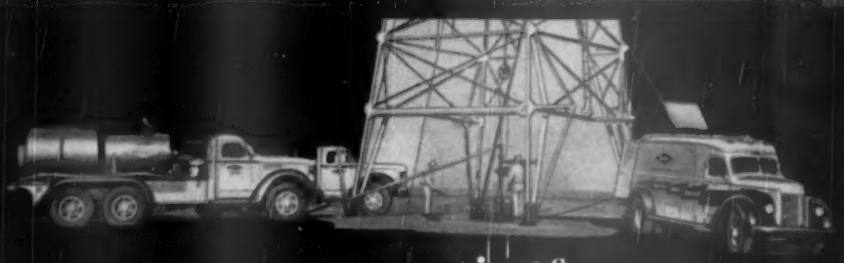

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Editorial Comment—

A MAGAZINE'S GOAL

By John E. Sherborne

Branch Chairman

THE JOURNAL OF PETROLEUM TECHNOLOGY is entering its second year. As nearly as we can tell from the comment we have heard, during its first year it has been prepared to the satisfaction of a large number of the members of the Petroleum Branch. It is the aim of your editorial staff, Editorial Board, and Executive Committee to continue to improve the magazine. It is our goal to make it the most attractive and authoritative organ representing the petroleum engineering profession.

Having set the goal, it is necessary to examine the means by which it can be reached most satisfactorily. Analysis of the elements which the magazine must possess in order that it most nearly provide for the requirements of its readers would indicate the following to be significant. First, the magazine should contain a news section by which the member can be apprised of current happenings of interest to the large majority of members. An editorial section should bring before him matters which concern his affairs as a member of the Petroleum Branch of the Institute.

The editorial section should also provide a medium for the presentation of adequate expression upon both sides of controversial issues of the day which directly or indirectly affect him as a petroleum engineer. A portion of the publication should be devoted to articles concerning non-technical subjects, semi-technical material, and reviews of subjects of immediate and direct interest to petroleum engineers but of such a nature that they do not belong with those papers to be published in *Transactions*. And finally, for a professional organization, the most important section of its official publication is that devoted to the presentation of the technical findings of the scientists and engineers working within the professional field. It is this section which will have lasting value and which rightly will form the subject matter for *Transactions*. The technical findings of the engineer and scientist together with those of his colleagues form the raw material with which he constructs his plans and performs the calculations essential to the solution of the technical problems which confront him today. Published results of his and his colleagues' scientific efforts are the basis for continued progress in the future. It is of utmost importance that we be consummate in maintaining the authoritativeness and technical excellence of this section.

Besides upholding the present high standards which have prevailed for the technical part of PETROLEUM TECHNOLOGY to date, it is our goal to continue to broaden its scope to include subjects of the widest interest to petroleum engineers. The advantage of making available in one reference source important technical reports as soon as they become available should be readily perceptible and continued effort will be made to improve the magazine in this respect. It is our goal to further the making of PETROLEUM TECHNOLOGY the recognized source of published material in the field of petroleum engineering.

Your editorial staff and Editorial Board are aware that it will not be possible to tailor the magazine to meet each individual member's desire. But it is our wish to make it as nearly as possible to your liking. Next to the effort that will be directed toward continued improvement of the technical section, greatest emphasis will be placed upon the securing of articles of general interest and review articles in as wide a range of technical variety as possible within the field of petroleum engineering.

FROM the comments which have been brought to our attention it would appear that the news portion is being prepared as you wish it and it is planned to continue it much along its present lines. In the editorial section also it would appear that the policy of presenting guest editorials from leaders in the petroleum industry has been well received. This policy will be continued.

We have indicated a goal and discussed a possible plan of action. Every effort compatible with the financial means at our disposal will be made to attain that goal. Much consideration is being given to methods of improving the financing of the magazine. It is intended that this matter will be discussed in later editorials.

The JOURNAL OF PETROLEUM TECHNOLOGY is your magazine, and as such, your responsibility. We believe the goal described is the goal you want. Whether such is the case or not you can contribute much to its success by apprising us of your reaction. ★ ★ ★

What Is The Future Of

—For Research

—For

By Morris Muskat

Gulf Research and Development Co.

WHEN it was first proposed that the subject of research in production technology be explored, it seemed an easy task. All that would be necessary, presumably, was that the story of production research be told, rather than sold. However, shortly after accepting this assignment the writer was perusing the recently published *Proceedings of the First Annual Institute on Oil and Gas Law*, and found to his amazement the following statement: "I am inclined to feel that geologists and engineers sometime impede, almost as much as they aid, unitization efforts. I am inclined to feel that their theories and estimates are sometimes given too much weight."

Now these remarks were not made by one who had an "axe to grind," or who had a political motivation, but by a vice-president of an oil company. True enough, they referred to special problems of unitization and to the engineer and geologist, rather than research. But since the engineer of today practices and applies the research of yesterday, it is evident that the research man must accept the role of co-defendant in the above indictment of the petroleum engineer and geologist.

While entering a plea of "not guilty," in full conviction of a clear vindication, if tried by a jury of its peers, what defense does research have to offer? Has it, directly or through the medium of the practicing engineer, become a meddlesome disturber of the peace and tranquility within the oil industry? Has it dogmatically foisted untried, unsound, and irrelevant theory and speculation upon a self-sufficient and perfect machine? Has it subversively projected a fifth column movement into a dictatorship of blissful ignorance?

Only One Objective

Production research has only one objective — the improvement of the processes of oil production so as to achieve maximum recovery at a minimum cost. It is not a political movement. It is not a social philosophy. It is not an economic dogma. It is a scientific endeavor. It is an industry-wide collective effort, though carried on by hundreds of individuals in the spirit of competitive enterprise.

Of course, the goal of production research has not been fully attained. It has developed no final and absolute answers. It has not yet become a quantitative discipline leading to exact and infallible conclusions. No research scientist, or engineer applying his developments, can claim that thus and so will happen in an oil field with the numerical certainty of the accountant. But he may and should rightfully insist that the probability of his unbiased predictions being confirmed is much greater than that of confirming the predictions of the untrained, undis-

Continued on Page 31

By Charles V. Millikan

Amerada Petroleum Corp.

IN ORDER to understand the past and the present steps of the petroleum engineers and try to see what should be done for the future, perhaps it is well to take a good look at the past.

I don't know where production engineering had its inception. Certainly Caron and Norton — particularly Caron — were worrying considerably about what makes oil production. That was mostly along in the 80's. In the bustle and hurry to get production, however, the technical side of it was practically lost completely, until about the middle teens.

Lewis broke out at the Bureau of Mines on discussions as to how the oil gets out of the sand. What makes it get out? How much do we get? And what to do about it? One of his first articles was "Increasing the Recovery of Oil." And his discussion at that time was primarily on artificial water flooding, which had been done, to some extent, in the Bradford field.

Not long after that, Jackson came very much to the attention and study, particularly, of the Bureau of Mines, in the early 20's. Practically all of the technical concentration on recovery was on water flooding, and on gas injection. The actual technical side of it probably first developed in Bradford on the artificial flooding. But it was certainly Jackson, particularly prominent in Oklahoma, who showed that gas injection was prominent.

Production Technology?

Engineering — For Management

By R. W. French
Sohio Petroleum Co.

First Income Tax Law

On March 1, 1913, the United States had its first income tax laws, and that contributed very substantially to the advance of petroleum engineering. So long as taxes were low, there was not much done about it. But during the war years, when taxes went up, then the depletion end of petroleum became quite important, and the Bureau of Mines went into that question and established a decline curve for many of the prominent oil areas over the United States.

Cutler came into some prominence in 1920, and particularly in 1924, in his study of decline curves, and more particularly his discussion of spacing. That will be discussed further later.

In 1922, Sweigert made some tests on back pressures to control gas-oil ratios. This particular publication came out in 1924. Henry Doherty, about that time, discussed the importance of gas unitization and it was still emphasized, particularly in Oklahoma, when there was a bill introduced into the legislature, to make it a requirement that every reproducing well in the state should be produced under back pressure primarily for the purpose of controlling gas-oil ratios. Something should be done, they felt, and without any technical background, other than a few observations, they decided that was the thing to do. That did not go through, however.

Continued on Page 32

IN MOST cases, management is production technology, slightly out of date in technique, perhaps, and perhaps polluted to some extent by closer contact with the dollar in its corporate embodiment. Therefore an attempt will be made to give one view of what management thinks production technology is doing, perhaps some of the things it is not doing, and what it should do in the future.

No doubt there are many different views. Moreover, management itself has great responsibility for the clear and effective use of production technology — for what it is going to do, as well as perhaps what it has done.

Now, what is production technology doing from management's viewpoint? Briefly, management is being constantly furnished new equipment and techniques for doing more work with less money. It is being furnished increasingly accurate estimates of such vital factors as unit tank oil initially placed for ultimate recovery to any assumed economic low optimum production practice.

These are the foundations for intelligent management planning, because management is seldom free from the necessity of using money selectively to carry out its plans and objectives. Within the bounds of lease, legal and political limitations, exploitation is planned heavily upon the development and lifting cost per barrel, versus the net revenue per barrel, or 1,000,000 cu ft, and the pay-out period. In other words, without the basic technological information, it is impossible to approach satisfactorily these critical indices, culminating in the future total earning estimates per dollar expended.

Early Industry Weak

Of course, the early industry grew without modern production technology, but we might think of its results being about as effective as civil war artillery fire, compared with the radar-detecting, automatically computed and controlled artillery fire of today. If any one wants statistical proof of the value of production technology — although it is only one determinant — let him review the production, consumption and price relationships of the petroleum industry within the last 20 years.

In connection with that, I would like to quote no less authority than E. L. DeGolyer, who said, "The known oil reserves of the world have reached their greatness only because of the technological skill applied to finding, producing, transporting, refining and marketing, and they will continue to be great only if these technological practices are continually improved and extended."

Today, production technology is and must continue providing means to help management meet the increasing costs and the inevitably depleting reserves.

Now, as to what production technology is not doing at present. Again,

Continued on Page 37

RICHARD W. FRENCH, JR.

Petroleum Branch Vice Chairman 1950

THROUGH a long trek from East to West Coast and back, and through a variety of jobs in business, industry and the Air Corps, Dick French has maintained a steady interest in engineering which has culminated in his present position as vice-president in charge of production for Sohio Petroleum Co. in Cleveland.

He came by this interest naturally, for his father was a mining engineer. Born in Colorado Springs in 1907, he attended public schools there, in Nevada and in California, and graduated from Long Beach Polytechnic High School in 1925 in an engineering preparatory course. Turning eastward then, he attended the University of Delaware, graduating in 1929 in mechanical engineering. Extracurricular activities there, such as the presidency of student council and his sophomore class, developed leadership abilities which he has applied steadily since. Summer vacations were spent learning the "practical" side of engineering, repairing machinery and making lithopone for a paint pigment plant, and as a wiper and oiler for one summer aboard "M. S. Gulfpride," plying between Philadelphia and Port Arthur.

After college, he joined General Electric as a student engineer, working primarily on marine and aeronautical engineering. This, coupled with widespread recognition of the airplane, excited his interest in flying so he joined the U. S. Air Corps in 1930 as a flying cadet. He completed primary and advanced training at Kelly Field and then served 14 months on active duty as an armament officer and assistant engineering officer. He has a treasured souvenir of this duty in the form of a silk scarf made from the parachute which saved his life when he was thrown unconscious from his plane during an accident in practice combat maneuvers.

UPON expiration of his active duty he joined the Continental Oil Co. in Ventura, Calif., where his first efforts were applied to the business end of a shovel handle. From that he worked up through practically every job in the oil fields to field engineer, and in 1936 was promoted to production engineer in the Los Angeles office. For the next seven years he directed all of Continental's petroleum and production engineering in California. One of the particularly low points of his experience there was when he and Charlie Millikan ran a special sub-surface pressure gauge diaphram into a 15,000-ft well, accidentally broke it off and had to leave it in the hole.

In 1943 he was moved to Ponca City as assistant manager of Continental's Production Department, where his work covered all phases of engineering and production operations as well as administrative duties. In 1947 he left Continental to join Sohio in Oklahoma City as chief engineer and assistant to the vice-president in charge of production. He was then elevated to that post in 1948.

His main thesis in engineering has been accurate and continuous determination of factual data on well, reservoir, and equipment performance, followed by thorough analysis to permit proper recommendation to management. So much has he stressed this thesis that to many associates he is known as "P I" French. Throughout his career he has thoroughly respected the importance of each individual.

DICK married his high school sweetheart, Miss Elizabeth Pond, in 1931, and her support in all of his business and professional activities has been a major factor in his success. Their children are Nicky, age 11, and a daughter, Stephanie, age 14. Their primary pastimes are music, from folk songs to opera, church activities and color photography.

Aside from frequent contributions to the literature, Dick has been active in API and AIME affairs for years. He was national chairman of the API Topical Committee on Production Practice in 1941. Following Pearl Harbor he worked full time for five months in coordinating California production for the Petroleum Administration for War. In 1943 he was chairman of the Production Technology Committee of the Petroleum Branch of AIME. We are indeed fortunate to have him as vice-chairman now, and can look to him for continued active support and service. ★ ★ ★

Before the Legislatures of the
Federal Government and the Several States

★ ★ ★ ★ ★

Docket No. 1
In Equity.

Taxation, ***Plaintiff***

vs.

Mineral Resources, ***Defendant***

★ ★ ★ ★ ★

A SUIT FOR DELINEATION OF BOUNDARIES

Brief by GRANVILLE S. BORDEN, a Friend of the Court

This brief is a reconnaissance report on some prospects in the field of taxation which can safeguard our Mineral Resources. The brief is a prospectus soliciting help and enthusiastic cooperation in the common task of developing these prospects in a manner which will be most beneficial to all parties—the owners, operators, employees, tradesmen, the federal and state governments, and the people of this nation.

IN the Constitution of the United States and in the Constitution of the several states, the people have delegated to their legislators the powers to levy taxes upon them. Notwithstanding certain constitutional limitations upon these powers, such as due process clauses and equal protection clauses, the power to tax is the power to destroy. These legislators, in whom the power to tax is vested, can aggravate inflation; they can cause depressions; they regulate our standards of living; they can destroy free enterprise; they can tax special groups and give the proceeds to other groups or foreigners; they can levy excises which will regulate any type of activity; they can, by devious means, confiscate and expropriate; they can, through discriminatory taxes, engender civil strife; they can make us vulnerable to foreign aggression; and last but not least, as shown herein, they can convert our Mineral Resources into waste.

Although few of our legislators have had experience in the business of finding, developing, and producing our fuels and basic raw materials from the earth, the presumption seems sound that they are curious and interested in these activities; that they welcome instruction, especially from informed citizens when given in good faith and with the intent to promote justice and equality for all our people.

In the light of these circumstances, what can we do? We should strive to instruct our legislators in the impact of taxation upon our Mineral Resources to the end that they, through their votes, can construct barriers inside our Mineral Resources to prevent irreparable damage from trespassing by taxation. We can as individual citizens offer instructions and training to our tax lawmakers.

There are many facts which every lawmaker should know as he surveys the traverse of taxation through our Mineral Resources. Some are of broad, general import; others relate to current, specific problems. Some seem elementary; others are quite complex and technical.

As *amici curiae* (friends of this court) some of these facts are recorded herein where they may be available for assignment to our tax lawmakers. The balance of this brief is a recital of some of these facts.

What Every Tax Lawmaker Should Know

1—The magnitude of our Mineral Resources varies inversely with the magnitude of the taxes levied upon them. Mineral Resources are natural deposits containing valuable ingredients which can be exploited profitably. When the proceeds from the disposition of the valuable ingredients of any deposit are inadequate to meet the costs of production, the deposit loses its label as a Mineral Resource. It is converted into waste. As taxes on Mineral Resources are increased, more marginal deposits are converted into waste. For example, if the recoverable grade of ore is $10 per ton and the production cost is $9.50 per ton, this ore becomes waste if the state imposes a severance tax of $1 per ton.

2—Many additional levies on our Mineral Resources have effected net losses in revenue to the government which imposed them. Our Mineral Resources are a substantial portion of our national wealth and a major tributary to the stream of our national income. The proceeds from the disposition of the valuable ingredients are distributed to government, as taxes; to labor, as wages; to capital, as profits and dividends. As labor receives its wages, the income is taxed; as capital receives its profits and dividends, the profits and dividends are taxed. If the profits are corporate profits there is a double tax—on the corporation and on the dividends distributed by the corporation.

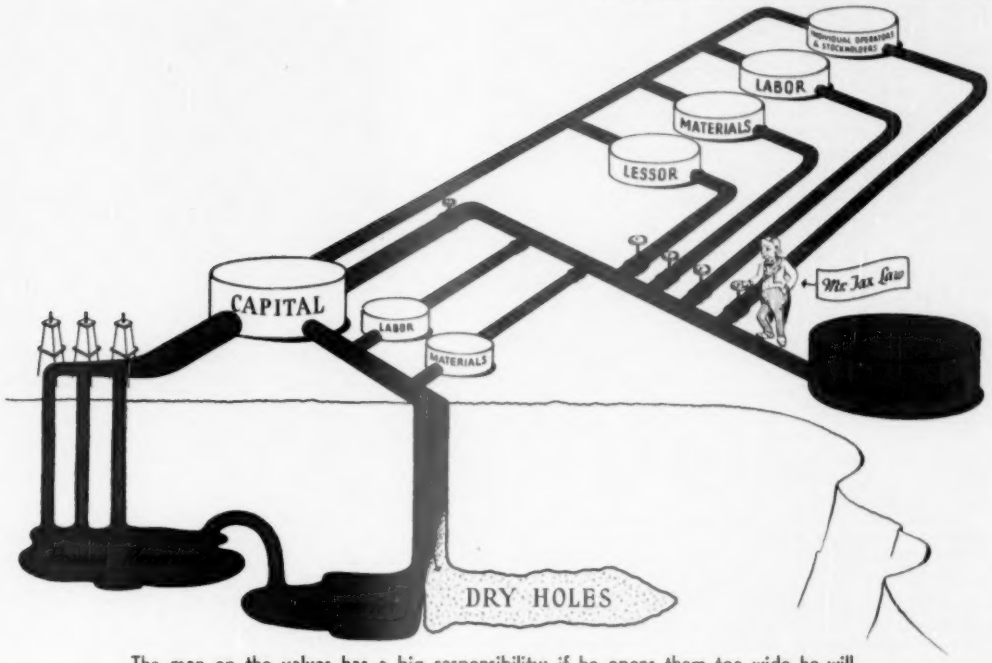
As the tax rates increase, Mineral Resources decline. When the burden becomes too heavy, mines and quarries are shut down, ghosts invade our mining camps, men lose their jobs, suppliers lose their trade, stockholders lose their dividends, processors and refiners lose their raw material, and Uncle Sam and the state lose their taxes on the profits of the operator, the wages of labor, the royalties of the owner, the profits of the tradesmen. Thus, although the tax rates have been increased, there is a net decline in the flow of revenue.

Not only does the loss of revenue ensue from the reduction in yield of income tax, but every increase in tax on the Mineral Resources effects some reduction in the fair market value of the deposit. With this decline in value, there are proportional declines in the yield of: (a) the *ad valorem* tax of the state, (b) the state's inheritance and gift taxes, and (c) the federal estate and gift taxes. Thus, although the tax rates have been increased, there frequently is a net decline in the flow of revenue.

Mr. Borden is a mining engineer, lawyer, and AIME Member from San Francisco, Calif. **This paper was presented at a Mineral Economics Division session during the AIME Annual Meeting, February 1950.** **The opinions expressed are those of the author and not necessarily of the AIME.**

3—Tax increases on our Mineral Resources reduce the number of discoveries of new Mineral Resources. Exploration is an expensive, speculative activity. Every tax increase tends to evaporate the funds available for exploration, and every tax increase tends to impair the incentives to enter or continue in this speculative and expensive exploration business.

If our standards of living are to be preserved, discoveries of new mineral resources are imperative: First, to set off the current depletion of known resources; secondly, to provide adequate reserves for growth in population under an expanding economy; and finally, as a stock pile to serve as a potential supply in time of war when



The man on the valves has a big responsibility; if he opens them too wide he will empty the pipe line faster than fresh supplies are discovered.

there are extraordinary demands coupled with man-power shortages.

No one can forecast how or when nature will yield the secrets of her underground deposits. Discoveries are not made under a time table, and the quantity and grade of the new deposits cannot be forecast by the best experts in the geological or economic sciences. All we know is the fact that the probabilities of discoveries depend on the amount of exploratory expenditures and the enthusiasm and wisdom of those who do the hunting. But no one spends money to hunt for worthless game emaciated from a superfluous tax diet.

4—Every discovery of a new Mineral Resource creates new sources of revenue for the federal and state governments, new sources of employment, new stimulants to trade, new sources of funds for more exploratory ventures, and new barriers against poverty and foreign aggression. We hear of "incentives" for the mineral industry. Why not speak of "grubstakes" for those who take risks to create new national wealth and national income? From time immemorial sovereigns have granted awards for outstanding services. The prospectors who create new national wealth should be the object of some governmental bounty.

Every discovery is made at substantial risk of loss. These risks increase in inflationary times as the quality and quantity of the prospects diminish.

If the government should feel justified in providing some grubstake for those who agree to explore, such action should not be deemed to be discriminatory against other taxpayers. There are many types of class legislation which extend special benefits in the name of the public interest—loans of the Reconstruction Finance Corp., farm subsidies, cooperative exemptions, the exemption from income taxes of all the income of labor unions, charities, educational institutions.

5—As additional taxes dry up the source of taxes, more taxes are imposed to meet the deficit; thus the merry-go-round of depression is accelerated.

Income Taxes

6—Every tax lawmaker should know that the producers of minerals, oil, and gas have not had a fair deal in the evolution of the federal income tax law; that the income tax burden levied upon them is, in many instances, discriminatory and unjust.—This discrimination arises primarily from the failure of Congress to recognize that a producer of minerals is in substance and reality engaged in two business enterprises. First, he is selling his mineral deposit. Secondly, he is in the business of mining. The over-all profits from both businesses are taxed as ordinary income at the normal and surtax rates; but if he sold the deposit to you and you mined the deposit, he would be taxed at the long-term capital gain rates on the difference between the sales price (value in place) and the cost.

We can concede for the purpose of discussion that the profits derived from the second business —i.e., the mining activity—should be taxed as

ordinary income, but the profit derived from the sale of the deposit should not be taxed more than profit derived from the sale of any capital assets.

To illustrate, in the case of a corporation, except relatively small corporations, the tax rate is 38%. Assume it paid $10,000 for some property and discovers a deposit worth $510,000. If this corporation sells the deposit to you, its federal income tax is $125,000 (25% of $500,000). If the corporation realizes this appreciation of $500,000 by mining the ore and selling this ore on the surface, it will pay on this realized appreciation $190,000 (38% of $500,000) less any reduction which may flow from the benefits of percentage depletion, which will be discussed next. Consider an open-pit mine. Why should the tax rate be 38% if corporation A, the owner, uses its own shovels and employees and only 25% if corporation A sells to corporation B, and the deposit is mined with the shovels and employees of corporation B?

Thus, if we grant that a producer is really selling his deposit as he mines the deposit, the conclusion seems clear that he should pay only long-term capital gain rates on this portion of his income. Congress by its failure to recognize this situation is effectively discriminating against our mineral producers.

It is noteworthy that Congress has granted taxpayers who cut timber the privilege of having their profits taxed at the rates applied to gains from the sale of capital assets.

7—Every tax lawmaker should know the facts which justify the allowances of depletion deduction on percentages of income.—On several occasions in the past, Congress has considered suggestions from the Treasury to repeal the provisions permitting determinations of depletion deductions on percentages of income from the depletable properties. On each occasion, after comprehensive hearings before Congressional committees, the Treasury's proposals were rejected.

In President Truman's tax message to Congress on Jan. 23, 1950, he stated that there is no loophole so inequitable as excessive depletion exemptions enjoyed by oil and mining interests.

This is a serious charge against our Mineral Resources. If it is true that there is an inequitable percentage depletion loophole in the law, it should be closed. If there is none—if these depletion allowances can be justified—then this Congress should follow the pattern of its predecessors when they rejected similar proposals.

The word "loophole" generally connotes some obscure, devious device of avoiding taxes, but the right to measure depletion by a percentage of income has been prescribed by statute for 25 years.

Percentage depletion is a complex subject, but some of the principal reasons for the allowance are briefly stated: Generally, percentage depletion fails to set off the discrimination against producers discussed in point 6 above. As a rule, if *A* mines his deposit, he will pay more income taxes, *even with percentage depletion allowances*, than *A* and *B* would collectively pay if *A* should sell to *B* and *B* should mine the deposit—a case where no percentage depletion would be allowed.

This gesture by Congress to equalize the burden and remove discrimination cannot fairly be lodged in the category of a loophole.

Statistics will prove that the tax savings which flow from percentage depletion are generally added to other funds and appropriated to determine where nature has hidden other deposits. These hunting expeditions are expensive and all the ventures speculative. The cost of finding new reserves is higher than the cost of finding the reserves which are being depleted. This is true not only because of general inflation, but also because of the gradual decline in the quality and quantity of prospects. The merchant can replenish his inventory by purchasing new goods, but the miner replenishes his underground inventory by speculating and wildcatting. For example, to maintain our present domestic crude oil reserves, the prospectors and explorers must find 2 billion additional barrels annually, and this task requires a lot of fortitude whether you are speculating with your own funds or the funds of your stockholders.

Many of the important discoveries of the past would not have been made had there been no percentage depletion. In the first place, the funds in reserve available for prospecting would not have been adequate to support the more speculative type of ventures. In the second place, without some tax incentives the long-shot plays would never have been taken.

Even admitting that the government is in the grubstaking business, a review of the past will prove that the producers have repaid these percentage depletion grubstakes with thousands of percent interest. **The loss of revenue to Uncle Sam from percentage depletion is in reality a capital investment to serve all the people through the promotion of their security and their prosperity.** The net results of the percentage depletion allowances are stupendous gains to the government. The yield to our government from new oil fields—such as Cuyama in California, and North Snyder in Texas—will set off all the revenue losses from percentage depletion for a substantial period. From the standpoint of insurance for prosperity, percentage depletion outranks any subsidies, loans, exemptions, aids or benefits which are granted by our government.

Corporate taxpayers lead the exploration parade. Granted that percentage depletion gives these corporate producers some tax savings, how do corporations utilize the funds that are saved? As stated above, these tax savings are reappropriated to search for new deposits. These expenditures, even though fruitless, engender new sources of employment and new stimulants to trade. If a discovery is made, the government shares in the benefits. Assuming, although it is not a fair assumption, that all of these tax savings are not appropriated for the search of new reserves, what is done with the balance? This balance is paid to stockholders as additional dividends where Uncle Sam takes back his share on this increment as normal taxes and surtaxes at the top bracket of the shareholder. The tax saving of the corporate taxpayer may be lost down a shaft, winze, or a drill hole with the proportional loss to our government, but it is never poured down a rathole.

Finally, have our people forgotten the contributions of the mining prospectors and oil and gas wildcatters toward winning World War II? Had there been no long-shot wildcat discoveries in the prewar days of World War II of oil, gas, copper,

lead, zinc, and strategic metals, we would be paying for a much longer war. Do they remember OPA; the "A," "B," "R," and "T," gasoline rationing tickets? Do they remember allocating metals and the hysterical search for strategic minerals? If their memories fail, let them refer to our current stock-piling programs.

After this narrow escape from disaster (wars cannot be won without adequate domestic Mineral Resources), can we afford to smother the enthusiasm of our prospectors and wildcatters to the end that our underground stock piles will become exhausted from ordinary peacetime consumption so that we will be caught short of these indispensable sinews of war when the next sneak attack occurs?

As shown in the prior discussion of general principles, the inevitable result of a heavier tax load on the mineral producers will be a net loss in national wealth and national income, an impairment of our security from poverty and our power to defend ourselves against foreign aggression.

If the parties who insist that percentage depletion is a loophole should review the record carefully, they will undoubtedly reach the inevitable conclusion that any revenue which flows out of this loophole returns to our government with a flood-tide of accessions.

8—Every tax lawmaker should know that the rules governing exploration and development expenditures by mining, oil, and gas companies effect inequitable and unjust results. He should know the technical reasons for these unfair results. He should know how remedies can be procured.—Why does tax liability vary in the treatment of exploration and development expenditures? Because these expenditures may not be deductions from gross income in the determination of taxable net income: (a) if the expenditure must be taken as an expense in a year when there is not sufficient gross income to absorb the income (or used as a carry-back or carry-over deduction), or (b) if the expenditure must be capitalized to be recovered through depletion deductions over years when the depletion deductions are based on a percentage of income.

There is a broad disparity between the rules which apply to mines and those which apply to oil and gas.

The general rule for mines in the development stage is set forth in Bureau Regulations 111 (Section 29.23 (m)-15 (a)):

> "All expenditures in excess of net receipts from minerals sold shall be charged to capital account recoverable through depletion while the mine is in the development stage. The mine will be considered to have passed from a development to a producing status when the major portion of the mineral production is obtained from workings other than those opened for the purpose of development, or when the principal activity of the mine becomes the production of developed ore

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High on the eastern slope of the Sierras is the tungsten mill of the U. S. Vanadium Corp., one of the few producers of this metal of economic and military importance. The law should provide for writing off exploration expenditures so that more sources of tungsten and other strategic minerals may be found.

Courtesy of Curtis Phillips

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Courtesy Standard Oil Co. (N. J.)

Few industries face such technical difficulties as are encountered in drilling for oil in the Gulf of Mexico. Here the Humble Oil Co. is drilling seven miles off shore. The rig has quarters, store rooms, storage tanks and maintenance facilities.

rather than the development of additional ores for mining."

The general rule for mines in the producing status is that development shall be treated as deferred development expense to be extinguished at a rate commensurate with the exhaustion of ore it serves. *General Counsel's Memorandum 13954*, C.B. 1934, page 66.

In the case of oil and gas there is no distinction between development status and producing status.

All expenditures "for wages, fuel, hauling, supplies, etc., incident to and necessary for the drilling of wells and the preparation of wells, for the production of oil and gas, may at the option of the taxpayer be deducted from gross income as an expense or charged to capital account." But any election is binding upon the operator for all subsequent years.

The rules pertaining to the treatment of expenditures for geological and geophysical expenditures by oil and gas taxpayers are extremely complicated. The treatment depends upon a mind-reading test whether land or leases were acquired or retained as a consequence of the geological and geophysical expenditure. If this is the conclusion, the expenditure is capitalized; if not, the expenditure can be expensed.

Why is all this confusion necessary? Why should these rules be invoked to deprive the producers of tax benefits? Clearly, every taxpayer should be entitled to deduct the money which he has spent for exploration and development either as a loss if no discovery is made, or as deferred expenses of exploiting the mines which have been discovered and developed. The law should provide rules which will grant a tax benefit for every cent expended for exploration and development and prohibit the impairment of these benefits through (1) the obligation to take deductions in loss years, or (2) through obligation to take the deductions as cost depletion so as to be merged into percentage depletion deductions.

Incentives can be engendered by removing unfair "decentives." If the Treasury is unwilling or unable (due to provisions in existing law) to rescind these decentives, our Congress should act.

9—Every tax lawmaker should know that the mineral producer is particularly vulnerable to hardships from an unjust rule relating to the recovery of depreciable capital established by the Supreme Court of the United States. He should know the remedy.—Under a rule established by

the Supreme Court of the United States, taxpayers may be deprived of the tax benefits which generally flow from the right to take depreciation deductions based upon the capitalized costs of the depreciable assets.

Briefly, under this rule, if losses are sustained in any year (or the net income before depreciation is less than the depreciation allowable), the taxpayer loses a portion of the tax benefits to which he is justly entitled under the general rule that the wear and tear on depreciable assets used to produce income are deductible in determining taxable net income.

The rule, commonly termed the Virginia Hotel rule, is an exceptional hardship on the producers of minerals, oil, and gas because this class of taxpayer generally loses his rights to procure deductions for net loss carry-backs of carry-forwards through obscure technical limitations in Section 122 (b), (c), and (d) of the Internal Revenue Code, which will be discussed below.

Many taxpayers are advocating a just rule which will permit taxpayers to deduct the cost of their depreciable assets from gross income of any taxable years—that is, the taxpayer shall decide how much of the remaining depreciable cost shall be taken in any taxable year until the total cost has been recovered. This rule would be fair and eliminate all the complexities involved in current practice, and cure the sting of the Virginia Hotel rule. Can this decentive be eliminated?

10—Every tax lawmaker should know that there is an obscure provision in Section 122 of the Internal Revenue Code dealing with carry-back and carry-forward net loss deductions which has unjustly cost the producers millions of dollars and will continue to levy, indirectly, a terrific unjust burden on our Mineral Resources.—The discourse is addressed to an obscure, unjust technical provision in the Internal Revenue Code which has cost the mineral industry millions of dollars and will continue to levy indirectly an unjust tax burden on their deposits. There is one gold mining company in California where these provisions increased their taxes by $134,000 for 1943, and there is another California company operating a tungsten-antimony-gold mine in Idaho where these provisions increased their taxes for 1943 and 1944 by $200,000.

The provisions to which reference is made are Section 23 (s) and Section 112 (a), (b), (c), and (d) of the Internal Revenue Code. Hidden obscurely away in these confusing and bewildering sentences is the rule that the *net loss* of any year when carried backward or carried forward to serve as a deduction from gross income of another year, must be reduced by the percentage depletion allowances in excess of cost depletion for the year to which the net loss is carried. The adverse effect of this rule can be expressed in either one of two ways:

(a) It deprives the mineral, oil, and gas producers of the major share of the benefits which

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It is not the technical problems or rugged aspects of the business which discourage the mine operator; it is the tax decentives which actually make it expensive to explore and develop over and above operating costs.

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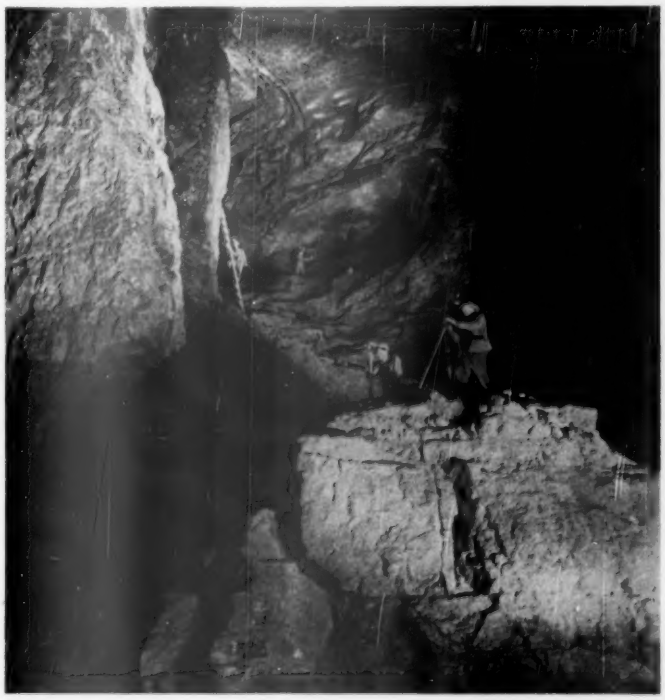

should accrue from the right to deduct net losses from the income of other years; or

(b) it indirectly repeals the right to a substantial share of the percentage depletion deduction for the year to which the net losses are carried.

The mineral producer falls in the category of feast and famine taxpayers who are vulnerable to wide fluctuations of income and losses over a series of taxable years. No other group of taxpayers are more equitably entitled to net loss carry-over and carry-back deductions. Nevertheless, these taxpayers, because of these obscure provisions in Section 122 of the Internal Revenue Code, can seldom procure any tax benefits from these provisions. The gold producers who sustained losses from War Production Board Order L-208 were the first group to lose refunds of prior year taxes because the losses sustained while operations were shut down were absorbed by the percentage depletion allowances of the year to which the carry-back loss would have applied. Next on the list of victims were the operators who mined stratetgic minerals at a profit during the war followed by an era of heavy losses in the postwar period.

Noteworthy is the point that the relatively small producers are the taxpayers most vulnerable to this inequity. Can this decentive be eliminated?

11—Income taxes can be assessed on the proceeds of new ventures before the operator has assurances that his investment will be redeemed.—The income tax law contains a provision in the section which allows deductions for depletion that "In any case in which it is ascertained as a result of operations or of development work that the recoverable units are greater or less than the prior estimate thereof, then such prior estimate (but not the basis for depletion) shall be revised and the allowance under this subsection *for subsequent taxable years* shall be based upon such revised estimate." (Italics supplied.)

If reserves prove to be less in a subsequent year than previously estimated, the cost depletion allowances for the year of overestimate may not be adequate to absorb the net income computed without the depletion deduction. Then, the operator pays an income tax. In later years, when as a result of "operations or of development work" the prior overestimate of reserves is demonstrated, the error cannot be corrected retroactively. The revised estimate of lower reserves can be used in determining depletion allowances and income taxes for "subsequent years" but no refund (except where carry-back losses may be deducted) can be procured of the taxes determined by using the erroneous high estimate. If the reserves as estimated prove to be inadequate to provide redemption, the taxpayer is out some income taxes even though the venture has not provided redemption of the amounts invested. Can this decentive be eliminated?

12—An investor in the shares of a corporation engaged in producing minerals, oil, or gas, may be assessed income taxes on dividends even though the amounts received are in fact redemption of the cost of his shares.—When a corporation distributes money or property to its shareholders, the test whether the distribution is taxable as a dividend (i.e., as ordinary income) or whether the distribution is redemption of the shareholder's cost of the shares is made from the financial status of the corporation; i.e., whether the corporation has undistributed earnings or profits, etc. The test is made without references to the cost of the shares to the stockholder. Thus, in many cases the shareholder must pay an income tax on all distributions which he receives from a corporate producer of minerals, oil, or gas, until the corporate property is fully depleted and liquidated.

For example, take the case of a purchase of stock in a mining company which is profitably mining an ore body—one which has small invested capital but substantial earnings from a limited ore body. All distributions are dividends and taxable income to the shareholders regardless of their investment in the shares. This is a rule of law, although in substance a portion of every distribution should be considered as redemption of the shareholder's cost of the shares to the end that the stockholder will procure complete redemption at the end of the life of the ore body and pay income taxes only on the increment of the distribution above the redemption requirements. Under existing law, the individual shareholder will pay income taxes on all the dividends at individual normal and surtax rates during the life of the enterprise, and upon its liquidation and termination he will sustain a long-term capital loss subject to the limitations on the amount deductible. Can this decentive be eliminated?

Conclusions

In conclusion, it is submitted:

1. The health and vitality of our Mineral Resources are in jeopardy from trespassing by taxes.

2. The duty and power to delineate boundaries and construct barriers against this invasion has been delegated to our tax lawmakers.

3. There are both elementary and complex facts pertaining to the taxation of minerals which every designer of mineral tax law should know.

4. Every citizen owes a duty to his country to help in this chore of teaching our tax lawmakers facts about our Mineral Resources to the end that they shall design and construct our tax laws intelligently—laws which will engender benefits for capital, labor, consumers, our state governments, our federal government, and every citizen of the United States.

STAINLESS STEEL CONTAINERS FOR LABORATORY DRILLING MUD TEST WORK

W. B. LILIENTHAL, MAGNOLIA PETROLEUM CO., DALLAS, TEXAS

A considerable saving in time and money has been effected by use of a specially designed stainless steel container for laboratory drilling mud test work. This container involves use of a standard tall-form stainless steel beaker for service in which the mud sample is heated to an elevated temperature and maintained there for protracted periods of time, while undergoing agitation to facilitate mixing of mud components. Agitation is accomplished by rotating the filled containers on motor-driven rollers within an oven. Several porcelain balls are generally placed in the containers to further improve agitation.

Soft glass containers (Mason jars) were used in this service in early work, and were found to be unsuitable for the following reasons:

1. Poor resistance to thermal shock.
2. Containers could withstand only relatively low pressures.
3. Accidental breakage in handling.
4. Chemical deterioration and subsequent mud contamination from reaction of high pH muds with the glass at elevated temperatures.

Pyrex containers were also considered, but, inasmuch as they provided improvement only in items 1 and 4 listed above, the additional cost was not believed to be justified.

A scale drawing of the container is shown in the figure illustrating details in cross-section. A pressed stainless steel lid was fabricated to match the rolled edge of the beaker top, and male and female screwed connections external to the container were made up to complete the closure with the O-ring used as a gasket between the lid and beaker. The brass screwed connections were made from extra heavy brass pipe, and were knurled on their periphery for ease of handling. In order to insure sealing, it was necessary to make certain that the beaker top was perfectly round in cross-section. After this condition was checked and corrected on a lathe if required, the container was ready for assembly. With the closure made up "hand-tight" the container was tested pneumatically at 20 psig. This container was made up with a 500 ml beaker to facilitate handling of customary 350 ml pilot samples, but almost any standard-sized beaker with a rolled lip may be used equally well, since O-rings are available in a large variety of sizes. The lower ring on the container was added so that the unit would ride evenly on the motor-driven rollers in the oven.

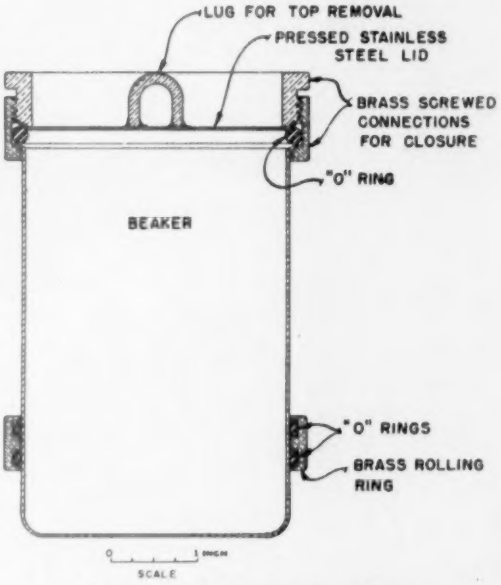

Fig. 1 — Stainless steel mud container.

These containers have given highly satisfactory service over the past six months in that no samples have been lost due to faulty closures, and no unusual difficulties in reassembly or in failure of parts have been involved. Although the initial cost of these containers is relatively high by comparison with costs for conventional soft glass and Pyrex containers of similar size, it is believed that the savings in time and samples and the additional safety of the metal containers more than justify such costs. ★ ★ ★

1950 WEST COAST MEET MOVES INTO THE PLANNING STAGE

Hosts Scheduling Big Things For October 12-13

The wheels of preparation are already beginning to turn in areas west of the Rocky Mountains as members of the Pacific Petroleum Chapter make ready for the annual West Coast Fall Meeting to be held October 12-13 in Los Angeles' Elk's Club.

Occurring a week after the 1950 Mid-Continent meeting in New Orleans, the two-day session will give West Coast Petroleum Branch members a convenient opportunity to hear outstanding men in the industry read up-to-date papers. Tentative plans call for 10 such papers to be presented in four sessions. This plan stands to be expanded if other high-quality material presents itself.

Host Chapter Chairman N. van Wingen promises that the "City of Angels" will be its usual self in offering pleasant atmosphere to attract an estimated 400 members to the 1950 meet, equaling the 1949 attendance mark.

The customary procedure of having a two-day morning and afternoon Technical Session Meeting will be followed this year as in the past.

On October 12, opening day, the Chapter has scheduled an elaborate luncheon in the plush Town House. Based on past reactions, this extracurricular event stands out as a near must on everyone's list.

Capping the social activities planned by the hosts will be a recurrance of the dinner dance in the popular Biltmore Hotel's Rendezvous Room. Those at the 1949 meeting remember the occasion as one of the highlights of the entertainment features arranged by the Pacific Petroleum Chapter.

All meetings and sessions will be held in the monumental Elk's Club building pictured on this page. The structure is situated across the street from a beautiful park that is typically Californian. The distractions are few in the locality and the quiet surroundings are relaxing as well as conducive to orderly sessions.

General chairman of the meeting is H. N. Marsh of the General Petroleum Corp. Sub-chairmen who he has gathered about him are R. L. Parsons, program committee; Herman Schaller, exhibits committee; R. D. Townsend, Jr., arrangements committee; E. A. Galvin, luncheon committee; John R. McMillan, dinner dance committee; and J. F. Alexander, publicity committee.

These men are dedicated to making the 1950 West Coast meeting one of the best on record, both in quality of papers presented and in orderliness of presentation.

Despite the sprawling limits of Los Angeles, most of the activities concerning Petroleum Branch members will take place in a central location and convenient to recommended hotels.

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SOUTH PLAINS SUB SECTION

Well Spacing Is Keller's Topic at South Plains Meet

By Robert R. Shaffer

Eighty members of the South Plains Sub-Section heard W. O. Keller, reservoir engineering supervisor for Stanolind Oil and Gas Co., read his co-authored paper entitled "Critical Analysis of the Effect of Well Density on Recovery Efficiency" at the group's March 16 meeting.

Keller, along with F. H. Callaway, also of Stanolind, are currently visiting many Local Sections with their paper that attacks the Cutler theory of well spacing. The paper deals with the engineering aspects of the problem and was originally presented at the 1949 Branch meeting in San Antonio.

The paper was reviewed extensively in the March issue of the JOURNAL. The discussion period which followed the talk at the South Plains Sub-Section meeting attested to the popularity of the paper in that it would have continued for several hours had time permitted.

Members of the Sub-Section have frequently expressed a desire to discuss in more detail the material presented at the meetings. Study sessions therefore will be arranged in the near future to accomplish this purpose.

Under the leadership of J. D. Christner and K. L. Smith, Stanolind has conducted classes for the benefit of its engineers and roustabout engineers in Levelland, Texas. The program in which engineers from other companies have also shown an interest includes work in reservoir engineering problems, interpretation of well logs and a study of corrosion problems.

Within a few weeks, Smith and R. M. Leibrock will have completed that part of the program pertaining to reservoir engineering. It is anticipated that the remaining parts will be presented at the study sessions in conjunction with the Sub-Section activities.

A questionnaire was also prepared and distributed at the March meeting by Leibrock, first vice-chairman. It was designed to aid in selecting topics and speakers for the monthly meetings. The most popular topics, as indicated by the questionnaire, will be published in an early issue of the JOURNAL. ★ ★

MORE SPACING TALK is indulged in by, L to R, Dick Coburn, Atlantic Refining Co.; W. O. Keller, Stanolind; Ray Chancey, Western Co.; and C. E. Smith, also of Western.

EAST TEXAS SECTION

Advocate of Wide Well Spacing Reads Paper Where Derricks Overlap

By P. G. Burnett

The seemingly popular paper entitled "Critical Analysis of the Effect of Well Density on Recovery Efficiency" by W. O. Keller and F. H. Callaway, both of Stanolind Oil and Gas Co., which has been read and reviewed at other Local Sections recently was enthusiastically received by the East Texas Section membership at its most recent meeting in Kilgore, Texas.

The paper was read by Callaway who with the co-author attempted to show that little additional oil can be recovered on close spacing in a depletion type reservoir.

Ironically, the paper was presented in a locality "where derrick legs interlace and walking beams pump wells from both ends."

By way of introduction, Callaway stated that the well spacing problem is primarily one of economics, i.e., the optimum well spacing is that which will yield the optimum return on the investment.

These economics may be different for various companies which have different amounts of money available for drilling. However, Keller and Callaway's paper is limited to the two engineering problems involved, namely, the effect of well spacing on oil recovery and on the rate at which oil is produced.

Continued on Page 37

RICHARD J. GONZALES
"Where do we go from here?"

GULF COAST SECTION

What's Happening in The Oil Business

By J. E. Kastrop

What has happened to the oil industry in the past few years, and why, and where are we going from here was the theme of the Gulf Coast Section's meeting of March 21. Approximately 125 members and guests were present to hear Richard J. Gonzales, economist, Humble Oil and Refining Co., discuss "Current Trends in the Petroleum Industry."

Gonzales introduced his subject by presenting what he termed two significant facts: (1) Production this month in the United States is at about the same level as it was three years ago. (2) Production this month in Texas is back to the level of the fourth quarter in 1945. In this long interim, a large excess producing capacity has been built up. Since that time about 365,000 oil wells have been drilled in the United States. From January, 1949, until March, 1950, there has been a decrease of about 26 per cent in the United States. In this period, Texas suffered a 15 per cent decrease.

To explain this situation, the post-war period must be analyzed. During 1946, there was a fast adjustment in business from wartime activities to peacetime operations. During that time, the oil industry made little adjustment. Heavy civilian demands, due to removal of rationing plus the relatively cheap price of gasoline and petroleum products, more than made up for the wartime military demands for oil.

During 1947, the largest volume demand for oil was made, representing an increase of 11 per cent over 1946. The industry was geared to only a five per cent increase, thus we were hard pressed to keep pace with 1947 demand, and the price of oil shot ahead. In 1948, the demand went up only four per cent, while the supply of oil increased nine per cent. During that year, 300,000 barrels of oil daily were added to oil stocks already in storage, representing a 20 per cent increase in tank oil for the year. In 1949 there was only a slight increase in demand and a decrease in oil exports. During that year, there was a 10 per cent decline in the industrial production index of the country which carried the production level back to the level of 1946.

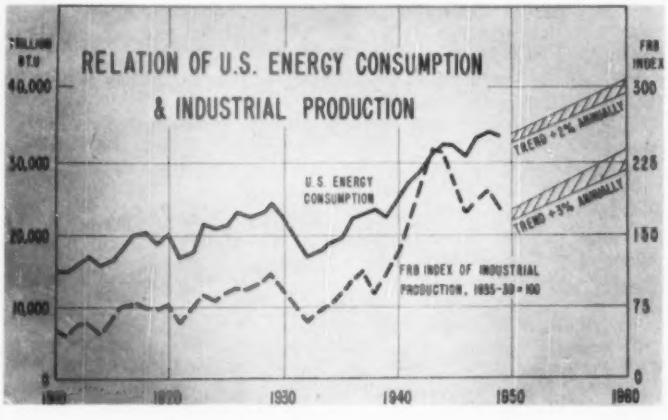
There was an increase in the use of natural gas which resulted in an impact on the oil industry. There was also a technological change that effected the volume sales of oil products. Railroads on the West Coast in other sections converted from oil-burning steam engines to diesels. Since one barrel of diesel fuel will do the job that four barrels of fuel oil previously performed, a substantial volume reduction resulted.

The average decrease in daily production during 1949 of about 470,000 barrels is equal to the total of 300,000 barrels of oil added daily to storage in 1948, plus the increase in 1949 of 170,000 barrels daily in imports. Texas took about 90 per cent of this decrease in production.

The subject was illustrated with a number of slides depicting the economic trend. The percentage change in demand for oil, gas and coal showed that in 1947 the oil and gas industry gained more than 10 per cent with gas gaining more than oil. During 1948, demand for oil dropped from 10 per cent to five per cent under 1947 demand, while natural gas dropped from 13 per cent to 10 per cent.

In 1949, oil broke about even with 1948, while gas increased slightly and coal took a terrific drop in demand.

Gonzales showed that the relation of U. S. energy consumption and in-



dustrial production correlated rather closely. Energy consumption of the nation in 1929 was 23,000 trillion BTU. By 1939, this figure dropped to 21,300 trillion BTU. During 1949, the energy consumption in the U. S. increased to 31,700 trillion BTU, the gain being accounted for in large part by oil and gas. Coal gained only slightly. Coal was lower in volume consumed than in 1929. The per cent of United States energy supplied by oil gained in position as the price of oil declined with relation to the price of coal. United States demand for petroleum products in 1929 was 2,576,000 barrels daily, compared to 3,373,000 in 1939 and 5,792,000 in 1949. The greatest increase from 1939 to 1949 was made in gasoline, distillates and residual fuel.

On the import-export situation, Gonzales showed that in 1949 this country's imports amounted to an average of 642,000 barrels daily, while the exports average only 327,000 barrels daily, making this country a net importer for three consecutive years. In winter, more residual fuel oil is brought in. The gap between imports and exports is ever widening, he pointed out.

As to the immediate future, Gonzales said the demand for oil in the first two months is good. Demand for gasoline is up slightly less than four per cent. California's gasoline consumption is down. Consumption of middle distillates is increasing, and residual fuel oil is coming back strong. During the year, the demand for coal will continue to lessen, while gas will increase, with oil going up slightly.

There will not be too much change in energy consumption in the United States. Oil has always moved ahead at an average increase rate of about five per cent annually. It is now down to three per cent. Therefore, the increase in demand will be from two to four per cent for 1950 over the past year. Gonzales pointed out that this could be supplied by imports. Action by the British Government in closing its doors to dollar oil has put tremendous pressure on foreign dollar oil. The United States is the biggest market for such oil, and there is no doubt, he stated, that imports will go up.

Production for March is 200,000 barrels daily less than the average in 1949. Production should come back to last year's average. Natural gasoline liquids will increase, with gasoline still strong, gaining perhaps three to five per cent. Middle distillates will increase substantially, depending on weather conditions. Being cheaper than coal, residual fuel should gain a little. The industry continues to restore oil reserves at a faster rate than oil consumption.

Most industries prefer to operate at 90 to 95 per cent capacity, while the oil industry in 1948 was operating at 100 per cent capacity. During 1949, the oil industry was forced to operate at less than its full capacity. Gonzales pointed out that demand does not fix price so much as the per cent of operating capacity of any industry. The further away from full capacity operations in any industry, the greater is the tendency to alter the product price.

Gonzales is recognized throughout the industry as one of the outstanding economists in his field. He was awarded his Ph.D. in economics from the University of Texas in 1934, after which he taught economics.

Since 1937 he has been economist with Humble Oil and Refining Co. Gonzales is chairman of the Economics Committee of the Interstate Oil Compact Commission. He has been a member of the Statistical Advisory Committee of API, Economics Subcommittee of the Petroleum Industry War Council, and PAW's Statistical Subcommittee for District 3. He is also a member of Phi Beta Kappa, American Economic Association, American Statistical Association, American Academy of Political and Social Science, American Petroleum Institute and others. ★ ★ ★

Clark and Walker Explain Material Balance Symbols

N. J. Clark of Humble Oil and Refining Co. and J. W. Walker of Shell Oil Co. explained the symbols used in the generally accepted material balance equations at a meeting of the AIME Reservoir Engineering Study Group March 9 at the Shell Research Laboratory in Houston.

As evidence of the amount of interest in the subject, "The Application of Material Balance Equations," approximately 65 engineers from the Houston area attended.

Clark and Walker initiated the discussion by showing how the various terms in the equations added up to a balance between the original oil and gas cap volume and the sum of residual oil and gas produced oil, gas, and water and volume of water influx.

Following this introduction of the subject, Walker took over the discussion and showed how a combination of laboratory P-V-T data and field production data was used in the material balance equation. He explained how P-V-T data taken at various intervals should be corrected to supply the needed information, and pointed out that one should not expect to get a reasonably accurate answer from the balance equation unless complete and accurate records are kept of all oil, gas, and water production throughout the life of the field.

This is often not done, particularly when field ownership is diversified and in the rush to drill and produce wells, initial reservoir pressures and production records are not carefully recorded. In those cases where good data is used, however, Walker showed that consistent answers can be obtained for the oil in place.

Throughout the evening, the audience took an active part in the discussion. It was brought out that good bottomhole pressure data was often difficult to obtain and some doubt exists as to how best to correct the pressures to a fixed datum plane.

In answer to a question as to how soon the material balance equation can be applied, Walker stated that, in general, at least 10 per cent of the reservoir must be produced before consistent answers can be obtained. By then it is usually known whether the field has an active water drive and the extent of water influx can be calculated. ★ ★ ★

PACIFIC JUNIOR GROUP

Moving a Rig Over Land and Water Off California Coast Proves Tricky

By Harold E. Nissen

In June, 1948, the Signal Oil and Gas Co., Honolulu Oil Corp. and Macco Construction Co. undertook the drilling of three wildcat wells on Santa Rosa Island.

Responsible for the engineering and planning that was necessary to transport a complete drilling rig and camp from the California mainland to Santa Rosa was Ernest O. Kartinen, chief of Signal's Construction and Maintenance Department. At the Rio Hondo Country Club in Downey, California, on March 9, Kartinen described the broad-scoped operation before a meeting of the Junior Section of the Pacific Petroleum Chapter.

Colored motion pictures, which were taken by the speaker, were used to illustrate the methods used to move the equipment both on land and across water.

Santa Rosa Island is the second largest of four which jut up out of the Pacific to form the Santa Barbara Islands. It is approximately 20 miles long and eight miles wide. It is mountainous with its highest point about 1600 ft above sea level, the stretch of terrain being divided into a north and a south side by a ridge running the length of it.

For the most part, this island is covered by grass, there being some trees in the more sheltered canyons and slopes on the eastern end of the island. Santa Rosa cannot be approached from the sea except in a few places because of the rocky beaches and steep cliffs rising from the beach almost perpendicular to a height of 30 to 100 ft. There were numerous springs in the canyons which in normal times supplied water for the cattle, but in 1948 everything was dry, and the chances of developing water from this source for drilling purposes looked very discouraging.

The Standard Oil Co. had drilled a well on this same island in 1932 and there was a wooden pier and a resemblance of a road part way across the island. Upon inspection the pier proved to be adequate for handling only relatively light loads. The only roads were so-called jeep trails which could be traveled only by short wheel base, four-wheel drive Army equipment. The three drilling sites were on the western end of the island.

The first month of activity was spent in field work and gathering data on the entire venture. The problems of transportation of heavy equipment, everyday supplies and personnel, were the most important. Every operation depended in some way on transportation. Construction of some 18 miles of road, development of a suitable water supply for drilling, and the construction and maintenance of a camp capable of handling at least 50 men were necessary. These were the important problems for which answers had to be found.

Santa Rosa Island lies on an East-West axis parallel to the coast line of California which at this point runs in an east and west direction. The islands of Santa Rosa and San Miguel are the westernmost islands in this group and extend out into the Pacific Ocean beyond Point Conception and some 80 miles from San Pedro.

After a brief stay on the island it soon became apparent that one of Mother Nature's forces which had to be always considered was the wind. Although the drilling sites were located on the western end of the island, and at first glance at the problem, it seemed logical to conduct operations from this end, calling for the construction of five miles of roadway and making the drill sites relatively close to the beach, after a few weeks on the

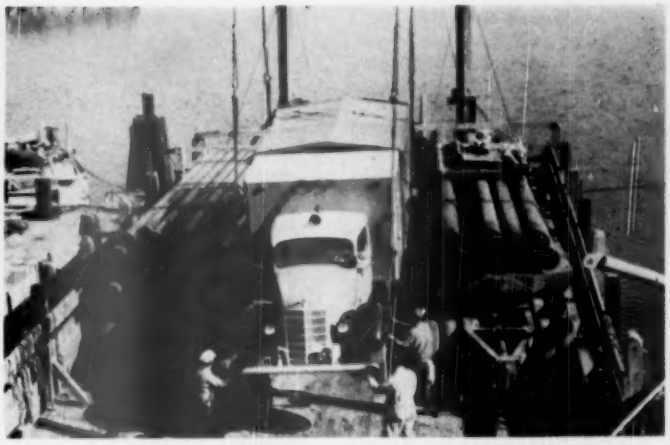
island, checking the beaches and possible roads up from the beach, along with a report on winds and waves made by the Scripps Institute of Oceanography, it was apparent that attempts to conduct any operation from the ocean on this end of the island over a period of several months would be very risky.

The only logical place on the island where it would be feasible to conduct landing operations was on the northeast corner at a place called Beecher's Bay. Here there are several hundred feet of smooth sandy beach and a road to the beach. This beach was 11 miles from the first location and 18 miles from the last location.

After a careful study of the terrain, aerial and reconnaissance trips, it was decided to use the existing road for a distance of five and one-half miles. This road followed a ridge up to the top of the island's highest peak, some 1600 ft above sea level. From this peak went another ridge which was followed with a road for five and one-half miles to the first location.

This original road went past an abandoned Army camp which had housed a radar crew during the war. Some of the buildings were still there minus doors and windows, floors, light fixtures, etc. The operators received permission to use this camp and the entire operation then was planned to conform with all landing operations to be conducted through Beecher's Bay and using the Army camp for headquarters.

As stated before, transportation was the crux of the entire operation. The success of the venture depended upon the success in solving the transportation problems. The problem was twofold. The first step was to get the necessary equipment and materials to the island by water, and the second operation called for the movement of the drilling equipment, supplies, etc., through the winter months over dirt roads in which grades as high as 16 per cent would be encountered.



PIPE AND TRUCK are loaded in San Pedro, California, onto a small barge which will span the water to Santa Rosa Island. The pipe is for drilling operations.

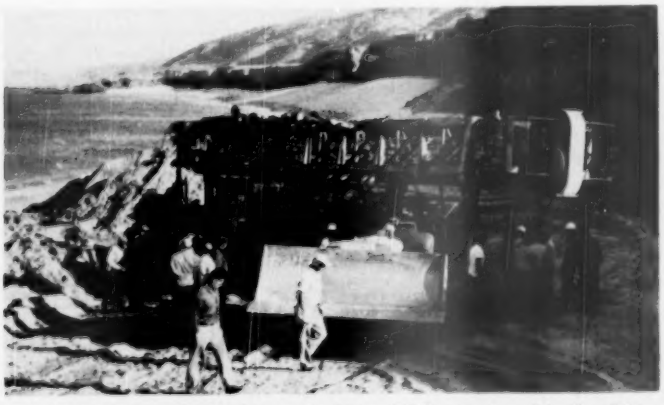
The drilling equipment was for the greater part conventional, most of it portable and skid mounted. The principal item was the drilling rig, a portable, trailer-mounted unit having a 96-ft telescopic quick-lift mast. Mounted on a 30-ton trailer, the rig consisted of a torque converter equipped air-controlled hoist, powered by a 300 hp twin diesel engine.

The weight of this unit was approximately 45 tons. The rated depth was 6500 ft, using 4½-in. drill pipe. The mud pump was a 7¼-in. x 12-in. unit, powered by a torque converter equipped twin diesel engine. The weight of the pump unit was 23 tons. Accompanying this equipment was the usual complement of tools, drill pipe, casing, cement, mud, and other supplies. The total weight of the drilling equipment was in excess of 300 tons.

Much has been heard about the wartime landing crafts and beach-head operations and therefore the possibilities of using some of the various types of landing craft on this job were investigated. They all proved either inadequate for the job or were too costly.

After some consideration it was decided to use ordinary flat wooden barges. These barges are 133 ft long, 42 ft wide, and 14 ft high. They were being used on the Long Beach breakwater to haul as high as 900 tons of rock at a time. They hauled about 100 tons per feet of submergence.

Loads carried on the barges had to be calculated for correct weight distribution as well as convenience of loading and unloading. Barge operations were conducted between the Los



UP THE HILL from the beach goes the 48-ton drilling rig, towed to the plateau up a 16 per cent grade by three bulldozers, one in front and two behind.

Angeles harbor and Santa Rosa Island. The loading and unloading operations at the mainland were relatively simple because of the good docks and hoists available. The landing operations on the island were somewhat more difficult. The operators were fortunate in that they had a gently sloping sandy beach. The surf, cross winds, and a three to four mile an hour current parallel to shore gave some uneasy moments.

Unloading operation on the beach required that the barge be beached at high tide and held there by steel cables and manila hawsers until the tide went down enough for the barge to be securely anchored to the beach. The large barge being 14 ft high required a sizeable ramp of sand over which to remove the load.

As to the time schedule, the island was first looked over on June 26, 1948. On August 17, the first load of big equipment was landed. On October 5, the drilling equipment was put ashore and the crew moved off on March 11, 1949, having in the meantime built 18 miles of road, laid 30,000 ft of pipeline, maintained a camp for 50 men which was several times filled to capacity, gone through as cold a winter as was remembered on the island and had snow which was the first recorded in 400 years (the last being recorded by Cabrille in his log).

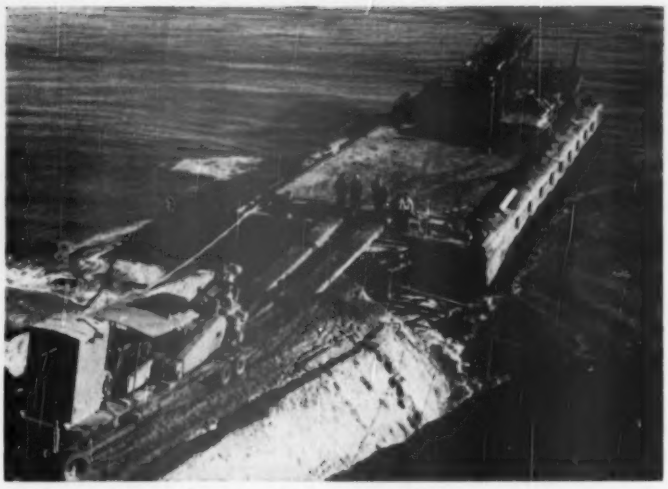
Sixteen barge trips were made to and from the island. Insurance was an important item and a total insured value of $987,500 was carried on the 16 trips.

Before Kartinen described the Santa Rosa Operation to the group, last year's chairman, C. T. McClure, opened the meeting in the absence of Norman B. Clark. He announced that I. A. Marshall, Jr., had been nominated by the executive committee to replace Norman B. Clark who has been transferred to Coalinga, California.

The nomination was seconded from the floor and in the absence of any other nominations, Marshall was unanimously elected chairman. He then introduced Harold E. Nissen and William G. Paul, Jr., as program chairman and secretary respectively.

The newly elected chairman then introduced the speaker of the evening.

* * *



FLAT BOTTOM BARGES come in handy to effect loading operations at Santa Rosa Island. Here drilling equipment is being moved off the island.

SOUTHWEST TEXAS SECTION

Landua Outlines Tester Developments

By H. D. Vaughan

Harvin L. Landua of Humble Oil and Refining Co. told members of the Southwest Texas Section at a recent meeting in Corpus Christi that wire-line-type formation testers must be used more to obtain data in order to evaluate results and went on to explain current development in this type tester.

Hearing Landua read his paper entitled "Developments in Wire-Line Formation Testers" were 206 Section members and guests.

The speaker said that industry-wide in the United States, it is estimated that drill-stem tests were being made at a rate of about 120 a day during October, 1949. In the operation of one oil company, drill-stem testers were used in 1948 in about 40 per cent of the total wells.

The test required an average of about 15 rig-hours and of their total cost approximately 67 per cent was for rig time and the remaining 33 per cent for service company charges.

Landua said that wire-line-type formation testers are being developed and given field trials because, if satisfactory, they will use much less rig time than conventional testers, they may replace conventional testers only to determine formation fluid content and they may encourage testing of poor quality zones that are now passed up.

The devices are limited to use on rigs that are equipped with both surface and subsurface wire-line coring equipment. In field trials mechanical operation of the present build of one type rathole wire-line-type formation tester was generally satisfactory and, in addition, obtained native fluid samples in three out of six trials.

A hydraulically-operated tool was used in two wells and demonstrated that the hydraulic method of tool-and-packer manipulation worked under actual field conditions and that the tool could obtain native formation fluid.

A combination sidewall core cutter and tester recovered formation cores but no formation fluid samples. Recording subsurface pressure gauges must be used with the testers to allow proper interpretation of results and a check of tool performance.

* * *

Pressure Maintenance By Water Injection Discussed Before Mid-Continent Group

About 69 members of the reservoir-study group assembled in Tulsa on February 21, to hear Kenneth Anderson, U. S. Bureau of Mines, Dallas, and member of the North Texas Section, discuss pressure maintenance by water injection in the New Hope field, Franklin County, Texas. Anderson's talk was based on Bureau of Mines R. I. 4594.

The New Hope field, discovered in 1943, has an oil productive area of 4950 acres as delineated by the drilling of 64 wells. Four oil-bearing reservoirs — the Bacon oolitic limestone, and the Hill, Pittsburg, and Elledge sandstones, all in the Trinity group of the lower Cretaceous series—have been penetrated at depths ranging from 7300 to 8100 ft. Three of these reservoirs were found to be closed-type or solution gas-drive reservoirs, and one, the Hill, was an open-type or water-drive reservoir.

Analyses of cores from the four reservoirs showed average porosities ranging from 10 to 18 per cent, average permeabilities of 17 to 297 millidarcys, and average connate water contents ranging from 25.4 to 30.6 per cent. Subsurface and recombined samples of reservoir oils indicated that the oils in the Bacon, Hill, and Pittsburg reservoirs were undersaturated with gas.

No subsurface samples of oil from the Elledge reservoir were analyzed, and because of meager data this reservoir was not studied in detail. The rapid decline in pressures in the four reservoirs during the first year of operation alarmed the operators and provoked them to investigate the reservoir conditions to determine the cause. As the oils in the Bacon, Hill, and Pittsburg reservoirs were undersaturated with gas, it was apparent that the propulsive forces driving the oils through the reservoirs were being supplied mainly by the expansion of the reservoir oils plus limited expansion or encroachment of edge water.

At the request of the operators, the Railroad Commission of Texas reduced the allowable production from the reservoirs in the spring of 1945. As a result, the declines in reservoir pressures were arrested slightly in the Bacon and Pittsburg reservoirs, and halted abruptly in the Hill reservoir.

These reactions of reservoir pressure to a reduction in the rate of withdrawal of reservoir fluids indicated that the Bacon and Pittsburg are closed-type or solution-gas-drive reservoirs that probably are surrounded by small volumes of salt water, and that the Hill reservoir is an open-type reservoir with a water drive that could be made effective if properly controlled.

It was evident, therefore, that the injection of extraneous fluids would be required to supplement the limited water drives in the Bacon and Pittsburg reservoirs and the more active water drive in the Hill reservoir. An adequate supply of gas was not available in the vicinity of the New Hope field, and water was selected as the pressure medium.

Fresh water and salt water, not commingled, were injected in closed systems without treatment into the Bacon, Hill, and Pittsburg reservoirs through five dually completed injection wells that had been converted from dry holes or nonproductive wells. Injection pressures in excess of 4000 lb psi at the wellhead were required to inject 500 to 600 bbl of water daily in a well through the relatively low permeable reservoir rocks.

Continued on Page 27

TULSA MEET CHANGED TO MAY 12-13

The date of the two-day Joint Meeting of Mid-Continent, Oklahoma and Kansas Sections, formerly set for May 5-6 has been changed again to allow all sections to participate at their convenience.

The new dates of the annual meeting are May 12-13. The meeting will be held at the University of Tulsa in collaboration with AIME affiliated Petroleum Engineering Clubs of the University of Oklahoma, the Oklahoma Institute of Technology (of Oklahoma A&M College) and the University of Tulsa.

The meeting will be opened Friday noon, May 12, with a luncheon for section and school group officers and speakers at the University's Student Union Cafeteria. From 12:30 to 1:30 p.m. registration will take place in the Phillips Engineering Building. Registration fee is $1. Students will not be required to pay a fee.

From 1:30 to 5 p.m. Friday, the first technical session will be conducted in Lorton Hall. Co-chairmen for the session will be Roy H. Smith of Stanolind Oil and Gas Co. and A. W. Walker of the University of Tulsa. President C. I. Pontius of the University will deliver the opening remarks.

During the session a selected paper from each of the participating schools will be placed in competition for prizes provided by the Petroleum Branch. Following the undergraduate student paper contest, the technical paper "Southwest Antioch Gibson Sand Unit" by T. E. Ockershauser of Globe Oil and Refining Co. will be read.

Another paper entitled "Recent Oil Shale Developments" by Boyd Guthrie, superintendent of the Bureau of Mines at Rifle, Colorado, will also be read during the session.

On Saturday, May 12, the second technical session will open at 9 a.m. in Lorton Hall under the direction of Co-chairmen Henry Waskowski, Magnolia Petroleum Co.; John C. Calhoun, University of Oklahoma; and A. E. Schlemmer, Oklahoma A&M College.

Two papers, "Correlation of Bottom Hole Sample Data" by Guy Borden, Jr., and Michael J. Rzasa; and "A New Method of Determining Connate Water" by E. S. Messer will be read. ★ ★ ★

Well Spacing Discussion Continues As Kaveler Casts A Negative Vote

By Kenneth F. Anderson

Another vote against the practice of drilling more wells in order to effect greater recovery was cast last month by H. H. Kaveler of Phillips Petroleum Co. at the North Texas Section's monthly meeting in Fort Worth's Blackstone Hotel.

More than 100 members and guests of the Section were present to hear Kaveler discuss the long-standing, controversial topic of well spacing. From the trend of discussion which followed Kaveler's talk, it could be concluded that a good deal more time will pass before agreement is reached regarding the subject.

The subject matter of the popular speaker's paper, entitled "More Wells, More Oil?," was directed to the question of whether or not additional recovery can be obtained from a pool or lease through the simple device of increasing well density by in-fill drilling.

The production histories of the Hotulke Hunton Limestone Pool, the Southeast Warwick Cleveland Sandstone Pool, the West Agra Clevelend Sandstone Pool and the Wewoka Lake Booch Sand-tone Pool were cited as field examples where well spacing was increased during the life of the fields.

In each field production histories were analyzed by the conventional log-log decline curve method which indicated that the increased drilling either resulted in no substantially increased ultimate recovery or resulted in less recovery due to increased wastage of gas from high gas-oil ratio wells.

The speaker emphasized that undoubtedly many other examples could be found if the records were closely examined, although it is often difficult to bring together the essential information in the older pools.

The in-fill drilling program of the industry following World War II undoubtedly will provide many examples of the relationship between ultimate recovery and well density if those interested in the subject will take the time and make the effort to bring the information together, Kaveler contended.

In the closing remarks the speaker charged that "the advocates of 'close' spacing have presented little, if any, field data to substantiate their generalizations. It is, therefore, effective to bring attention to the examples that do exist that confirm the well-founded technical conclusion that more wells drilled into a pool do not necessarily result in the production of more oil ultimately."

The Section meeting earlier was called to order by the newly-elected chairman, Roland Gouldy. During the business session, Gouldy gave a summary of his trip to New York where he attended the National Meeting of the AIME as a delegate of the North Texas Section.

William Stiles, vice-chairman for Dallas, announced the appointment of committees which will be responsible for the Section's activities in Dallas. These committee members are: Program Committee, A. Ed Caraway, T. S. Bacon and L. L. Baker; Membership Committee, Daton Clewell, Don L. Marshall and Thomas L. Kennerly; Hospitality and Entertainment Committee, J. H. Sullivan, Bob Seal and Dallas Hawkins.

Nelson W. Williams is to be in charge of publicity while Caraway, Clewell and Sullivan are to act as chairmen of their respective committees. ★ ★ ★

DEEP IN CONVERSATION before the North Texas Section banquet are, L to R, R. G. Parker, Continental Oil Co.; Sam DeWitt, Seaboard Oil Co.; Roland Gouldy, Section Chairman, Bridwell Oil Co.; and Patrick Reardon, Gulf Oil Co.

WARMING UP for his later assault on well spacing is Herman Kaveler, left, Phillips Petroleum Co. With him in Fort Worth are W. R. Berger, center, of Cummins, Berger & Pishny, and John R. Evans of Stanolind Oil and Gas Co., Fort Worth.

KANSAS SECTION

Salt Mud Log Discussed In Kansas

By W. F. Brown

L. G. Chombart, Schlumberger Well Surveying Corp., climaxed his talk to the Kansas Section, at its February meeting in Great Bend, with a presentation of the Salt Mud Log. This new type log, developed in Kansas in 1949, consists of a Gamma-Ray curve and one or two MicroLog curves. All curves are recorded simultaneously in one trip in the open hole, and the log does not require spotting of fresh mud. The Salt Mud Log can accurately locate the boundaries of all the formations and permeable breaks traversed, but cannot be used for fluid content interpretation. Although first designed for use in the Central Kansas Uplift region where the drilling muds become saturated with salt as the wells traverse thick salt beds of Permian age, the Salt Mud Log has recently extended its area of application to all regions where salty muds are encountered.

Chombart also reviewed briefly the basic principles behind a modern electrical log of the conventional type. By means of actual examples he pointed out the behavior of the S.P. curve and the resistivity curves in limes and dolomites, and contrasted this behavior with that occurring in shale and sand areas. He outlined the basic rules of interpretation in hard rock country, particularly with regard to the definition of formation boundaries and the location of permeable-porous breaks. The general relationship between the specific resistivity of a rock, its porosity, "cementation factor," interstitial water content and the salinity of that water was presented and discussed. The flattening out of the S.P. and resistivity curves in salt mud was explained. It was pointed out that in order to get a good conventional log, there must be a decided contrast between the salinity of the mud and that of the interstitial waters in the formations.

By means of numerous examples gathered in Kansas, Oklahoma, the Texas and Oklahoma Panhandles, North and West Texas, he showed how the MicroLog used in conjunction with a standard electric log permits an extremely detailed and accurate definition of the lithology and of the permeable breaks.

Approximately 50 members and guests enjoyed the buffet dinner and technical program, arranged by W. R. Warren, vice-chairman for Western Kansas, and H. R. Roberson. Warren stated he had received many requests from Western Kansas members to hold meetings once a month in Western Kansas, rather than once every three months as at present. After a short discussion a motion was made by Walt Pearson, Stanolind Oil and Gas Co., Ellinwood, to make Western Kansas a Sub-Section, within the framework of and conforming to the bylaws of the Kansas Section. The motion was seconded by Jack Gallivan of Wood River and carried without a dissenting vote.

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WAITING FOR THE MEETING to begin are Ray Gahan, Anderson-Prichard Oil Co., left, and Charles L. Fulton, Halliburton.

MID-CONTINENT SECTION

Continued from Page 25

The response to pressure maintenance by water injection was almost immediate in the Bacon limestone reservoir with the decline in the average reservoir pressure being arrested during the first three months, and an increase being observed one year after injection began.

Material-balance calculations made after each pressure survey illustrated the combined effect of pressure increase or reduction, withdrawal of reservoir oil, water injection, and water encroachment or expansion. The volume of water injected into the Hill reservoir was negligible, and the arrested decline in reservoir pressure was attributed to a reduction in the rate of withdrawal of oil from the reservoir. Water injection into the Pittsburg reservoir began at a slow rate, and the decline in reservoir pressure was not arrested until 14 months after injection began.

It is not necessary to restore the reservoir pressures to the initial values for full effectiveness, and they should not be increased beyond the pressures necessary to maintain production by natural flow, as that would retard natural water encroachment and increase injection pressures.

The beneficial effects of pressure maintenance in the Bacon, Hill, and Pittsburg reservoirs can be judged by the number of wells that were capable of producing by natural flow. The number of wells producing from the Bacon limestone reservoir by natural flow decreased from 13 to 0 before pressure maintenance and increased from 0 to 19 within a year after water injection began.

The volumes of oil that could be recovered ultimately from the Bacon, Hill, and Pittsburg reservoirs with or without pressure maintenance by water injection were estimated by applying selected recovery factors to the calculated initial volumes of stock-tank oil in the reservoir. These estimates showed that approximately 18,000,000 bbl of oil could be expected from the Bacon, Hill, and Pittsburg reservoirs by dissolved-gas drive without pressure maintenance, and approximately 37,000,000 bbl or a 100 per cent increase in recovery by water drive induced by the injection of water.

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The Drift of Things

...as followed by EDWARD H. ROBIE
Secretary AIME

A New Manager of Publications

As all employers know, it is one thing to get a good man and quite another to keep him. When Tom Lippert was engaged by the Institute as Manager of Publications last July under a two-year agreement it was hopefully believed that editorial, advertising, and circulation problems had been transferred to a head capable of solving them. Changes in the editorial content and appearance of the Journal of Metals and Mining Engineering soon became apparent and by the end of the year advertising was also looking up. In the February issues the first story of Cerro Bolivar — Venezuela's phenomenal new iron mine — made publishing history in the mining field. Then, immediately after the Annual Meeting, Tom was offered a most attractive opportunity in a field completely divorced from publishing — as general manager of the newly organized Titanium Metals Corp. It seemed a chance of a lifetime and the Institute could not well do other than accede to his wish to accept it.

The problem of a successor naturally immediately arose. The possibilities were rapidly surveyed, and the final choice was a man highly recommended by Tom Lippert himself, they having been associated together on the staff of The Iron Age. His name is Tom Lloyd, and he brings to the job much of the same experience as his predecessor though a few years less of it.

Lloyd began his duties on March 20, as Manager of Publications and Editor of the Journal of Metals. For the time being at least his sphere will not include the Dallas office.

Employment for Engineers

A new book entitled "Employment Outlook for Engineers" has just been issued by the Bureau of Labor Statistics of the U. S. Department of Labor (sold by Superintendent of Documents, Washington 25, D. C. for fifty cents). It should be of much interest to college students, educators, young graduates, and to those who employ engineers — in other words to a substantial proportion of the AIME membership. It is based on data supplied by some 25,000 engineers who participated in the survey. Engineers Joint Council cooperated.

Principal topics discussed are Employment Trends and Outlook, Earnings, and Occupational Mobility.

In the first sentence of the book we learned something: that engineering is the third largest profession, outranked in size only by teaching and nursing. For men, it is the largest profession. It is also one of the most rapidly growing professions and early in 1948 the number of engineers numbered about 350,000, or about three times the combined membership of the AIME, ASCE, ASME, AIEE, and AIChE. This should encourage the membership committees of our societies. By 1960 the number of engineers is expected to be 450,000. Demand for new engineers for the next few years should be 17,000-18,000 a year, but in the decade 1940-50 average graduations in engineering will number 19,000 annually. "The number of persons in training is at record levels and the number of graduates expected from these enrollments should more than supply the demands for engineers in the next several years." Last year 44,000 engineers were graduated, so it is evident why some of them had difficulty in finding jobs. Some 47,000 will graduate this year, so job finding may be even more difficult, but the number may drop to 36,000 next year and 29,000 in 1952. Even these lower figures seem considerably greater than the demand is likely to be though it is expected that in five years or so, demand and supply will be in balance. Mention is also made that men with special ability or training in research and design are likely to fare better than the average.

What should the schools do? Raise the standards of entry and use more exacting selection methods. Discourage the marginal student.

As to earnings, they average the highest for those with the greatest amount of formal education. "Masters" do slightly better than "Bachelors" and "Doctors" earn considerably more, but this may be because the better men go after the higher degrees. It seems to make but little difference whether one works for private firms or for the Federal Government, but state and local governments seem to pay less. Top-grade men do exceedingly well in engineering, but an engineering training is no guarantee of success for the mediocre. Unfortunately, 50 per cent of the graduates will always be in the low half of the class, but raising the level of the entire group will eliminate most of the mediocre.

Engineers do a lot of moving around from one job to another. That is well known as a general principle but here presented are data. AIME headquarters can attest to the fact, for our change-of-address desk processes about half of the membership every year. What is perhaps not so well known is the degree to which engineers change from one kind of engineering to another — such as from mechanical to mining. In 1946 more than 20 per cent of all employed engineers were work-

ing in a field different from the one in which they were trained. Of mining and metallurgical engineers, 27 per cent were working in other fields, the largest shift of any engineering group.

Chemical engineering is growing faster than the others. Civil engineering seems to be showing the slowest growth at present. "Reasonable" growth is expected in mining engineering, including petroleum engineering and metallurgy.

Salaries seemed slightly higher for mining and metallurgical engineers than for any other engineering group, but not greatly so.

All Except How to Make the Bomb

Latest of the scientific and engineering developments of the century is, of course, that of atomic energy. Automobiles, airplanes, motion pictures, the radio, and lastly television have in turn attracted the interest of many young men, but now those who are anxious to get in on the ground floor of the newest scientific marvel are attracted to the development of atomic energy. Older men, not trained in modern physics, have but slight knowledge of what this is all about. For both young and old who want to do some serious reading on the subject before the weather gets too hot we commend a new book of 228 pages published by the U. S. Atomic Energy Commission entitled "Atomic Energy and the Physical Sciences". (Superintendent of Documents, Washington 25, D. C., 50c). It is the best review of developments to date, current work that is going on, where it is being conducted, and who is doing it that we have seen. Fellowships and educational opportunities are included. If you are in the market for an isotope, or want to know how to recognize one when you meet it on the street, this is just what you need.

April Board Meeting on the 21st

Owing to the annual meeting of the Homestake Mining Co. in San Francisco on April 18, at which President McLaughlin must be present, and the annual meeting of the Canadian Institute of Mining and Metallurgy in Toronto April 17-19, the meeting of the AIME Board of Directors originally scheduled for April 19 has been postponed until the afternoon of Friday, April 21. ★ ★ ★

Personals

CHARLES C. HORACE is working for the Union Pacific Railroad in Wilmington, Calif., as a petroleum engineer trainee.

+

LON D. CARTWRIGHT, JR., chief geologist, Gulf division, Union Oil Co. of California, has been transferred to Los Angeles as chief geologist for the company.

+

A. I. LEVORSEN, geologist and former president of the Geological Society of America, has resigned as dean of the Stanford School of Mineral Sciences, Stanford, Calif. He will devote his time to teaching and research in petroleum geology.

+

A. E. GETTZENDANER, zone geologist, Gulf Oil Corp., has been transferred from Houston to Corpus Christi.

+

GEORGE W. TRACY, petroleum engineer for Stanolind Oil and Gas Co., has been transferred from Midland, Texas, to the Tulsa Research Laboratory.

+

W. R. LUND, Tulsa, Oklahoma, division production manager for Shell Oil Co., has been transferred to the regional production staff, where he will pursue an advanced training program.

+

C. W. TOMLINSON, Ardmore, Oklahoma, independent operator and president of the American Association of Petroleum Geologists, was guest of honor at a recent luncheon given by the Colombian Petroleum Institute in Bogota.

+

G. J. DECKER, district manager for Schlumberger Well Surveying Corp., at Hobbs, N. M., has moved to Edmonton, Canada, for a few months on a special assignment.

+

E. G. DOBSON, formerly senior petroleum engineer, has been made chief petroleum engineer of Texas Petroleum Co., Venezuelan division, with headquarters in Caracas.

H. W. HAIGHT, a vice-president and director of Creole Petroleum Corp. since June, 1946, has been elected executive vice-president of the company.

+

IRA H. CRAM, Houston, vice-president in charge of exploration for Continental Oil Co., has been named vice-president in charge of the production department. He will also continue in his present position.

+

H. H. HINSON, chief production research engineer of Continental Oil Co., has been promoted to assistant manager of the production department.

+

DONALD E. TROTT, petroleum engineer for Standard Oil Co. of Texas, Midland, has been transferred to Snyder, Texas, as drilling engineer.

+

M. M. LEIGHTON, of Urbana, Illinois, Chief of the Illinois State Geological Survey, has been elected to honorary membership in The American Association of Petroleum Geologists, as announced recently by C. W. Tomlinson of Ardmore, Oklahoma, president of the association. Symbolizing distinguished service performed in the field of petroleum geology, the certificate of honorary membership will be formally presented at the Stevens Hotel, Chicago, Illinois, on April 25, as a highlight of the thirty-fifth Annual Meeting of the A.A.P.G.

+

GRAYDON H. LAUGHBAUM, research geologist for the Central Division of Sinclair Oil and Gas Company, Tulsa, was guest speaker at the University of Oklahoma 10th Annual Career Conference on March 9. Laughbaum, a student in the first class in petroleum engineering offered at Oklahoma University, has been with Sinclair for 24 years.

+

DOW MIMS has gone to Calgary, Alberta, where he is general manager of the production department of the California Standard Co. He was with the Standard Oil Co. of Texas.

WHAT HAPPENED TO THE AIME DOLLAR IN 1949?

THERE'S BEEN A STORM BUT THE WEATHERMAN SEES 'CLEAR SKIES'

IN SPITE of everything else that the AIME may do, only two things probably seem important to the average member: the amount of his bill for dues, and what tangible things in the way of publications and meetings he gets for his money. Notable changes were made in both respects during 1949, which will be commented upon in this report.

Last year the Secretary's report dwelt on the reorganization that had proceeded in the Institute as a result chiefly of the recommendations made by the Johnson Committee at the Annual Meeting in 1948. This reorganization continued during 1949. All of the suggestions, ideas, and recommendations of the Johnson Committee have been studied carefully by the Directors and the Institute headquarters staff, and a large number have been adopted. More are in process of adoption, in at least modified form.

As was expected at the beginning of 1949, the AIME, for the third year in succession, suffered a substantial deficit. In 1947 this deficit was $28,000; in 1948, $82,000; and in 1949, $72,000. Fortunately the membership at large, the Directors, and the Institute staff united efforts in 1949 to end this formidable annual drain on reserves, and a balanced budget has been set up for 1950, with every expectation that a sizable surplus can be earned in 1951, and an even larger one in 1952.

Thus can the money borrowed from certain special funds of the AIME be returned to those funds. By the end of 1952 the Institute staff plans and hopes that income will be sufficiently in excess of expenditures so that the increases in dues that were voted for three years will no longer be necessary. In any event, the voting membership of the Institute will be the ones to decide. Perhaps the most important adverse factor in efforts to make it possible to return the dues schedule to its former level in 1953 is the prospect of continued devaluation of the dollar.

Such devaluation was arrested in 1949 but if the Government continues, in prosperous times such as we are now having, to spend some $5,000,000,000 more than it receives, and if labor unions continue to be successful in their effort to increase wage rates, the prospect for even a continuance of the sixty-cent dollar is not too bright. At least so it appears to some who still cling to "outmoded" ideas of economics and finance.

THE two largest items in AIME expenditures are for salaries and for printing and publishing bills. Upper-level salaries have not increased in proportion to the cost of living, but in the lower brackets the present salary levels reflect the devaluation in the dollar. Costs incident to publishing the magazines and books have probably increased more than has the average for goods and services.

In the financial report, income from dues is $226,000, which may be compared with $208,000 in 1948, an increase of 9 per cent. Advertising income was $86,000 compared with $63,000, an increase of 37 per cent. On the expense side, the cost of publishing the journals and Transactions, including the salaries of the editorial and business staffs, was $300,000, compared with $243,000 in 1948, an increase of 25 per cent.

This was in part because of a larger circulation but principally because of an increase in the amount of material published. The initial and promotional expense connected with issuance of three brand-new magazines in an attractive form that would appeal to members and potential advertisers alike was also a factor. All other expenses, aside from publishing, were $174,000 in 1949, a decrease of $11,000 from 1948, or 6 per cent, reflecting some economies that were made despite an increase of 8 per cent in the total membership that was serviced.

SOME members wonder where the money is found to meet deficits. It should be explained that the AIME has accumulated over the years some 25 special funds, with a capital amount of more than $800,000. The principal of practically all of these funds is inviolable, and the income from most of them is earmarked by the donors for special purposes. Fourteen of them have been established to give prizes and awards. Two or three have been set up to publish special volumes. Two or three must be used for the benefit of students and Junior Members; one is for scholarships; one is to help support the Library.

The income from special funds is not included in the income applicable to surplus unless specially appropriated by the Directors, usually with the consent of the committee that administers the fund. To meet the major part of the deficit incurred in 1949, some $7,500 was taken from the Rocky Mountain Fund and $6,000 from the Gemmell Memorial Fund, to finance Transactions volumes; $15,000 was taken out of the Life Membership Fund, made possible by the fact that the number of Life Members to be serviced has recently declined; and $35,000 was taken from the Special Fund for Publications, designed to maintain publications in times of depression, which leaves but little remaining in that fund.

Such sources of money to meet deficits are rapidly drying up. During the year the Institute learned that $1,000 had been bequeathed to it in the will of William H. Corbould, a British member who joined in 1892. Similar bequests have been of much benefit to the Institute in the past. ★ ★ ★

RESEARCH'S FUTURE

Continued from Page 6

ciplined and uninhibited exponents of authoritative intuition. Since the oil industry, as all other business activities, involves the element of risk, it is reasonable for the research scientist and engineer to expect that those who place the bets gamble on the most probable winner.

What has research accomplished? First and foremost, perhaps, is the establishment of the fact that each oil reservoir is a unique physical system, identical with no other except by a miraculous coincidence such as has not yet been observed. Each reservoir must be treated on its merits, rather than by a generalized rule of thumb.

Secondly, it has established a number of definable and determinable characteristics of oil bearing and productive rocks which are of significance in describing its productive potentialities. And it has developed the means and procedures for determining these characteristics quantitatively. These include the porosity, homogeneous fluid permeability, multiphase permeability, fluid saturations and the thermodynamic and dynamic properties of the reservoir fluids. Undoubtedly these are not all the pertinent factors which will ultimately be found. But they are among the important ones.

It Also Classifies

Third, it has classified the basic physical mechanisms and processes which may control the expulsion of oil from the reservoir rock and its production through the well bores. It has developed information directed toward the evaluation of the relative efficiencies of these mechanisms with respect to oil recovery. It has constructed theories of reservoir performance which serve to relate the roles played by these processes to the nature of the field development and operation. In this way it has facilitated the choice of optimum producing methods for achieving maximum recovery.

Fourth, it has developed instruments, procedures and practices for following the performance of reservoirs to evaluate their behavior and guide future operating programs. Bottom hole pressure gauges, bottom hole thermometer, the institution of periodic pressure surveys, pressure buildup measurements, the measurement of gas-oil ratios and water cuts, all provide reservoir data which research has proven will aid directly or indirectly in improving oil recovery.

Fifth, research has contributed to increased economy in drilling and completing producing wells. Improved drilling tools, more efficient coring methods and equipment, the development of superior drilling muds formulated and compounded to suit specialized drilling conditions, more effective cementing techniques, better fabrication and design of casing and tubing, more powerful perforation equipment, and the mitigation of corrosion difficulties, have all been stimulated or accelerated by research effort. And methods for well logging have been provided by concerted research effort to identify and quantitatively evaluate characteristics of the subsurface strata.

Admittedly these are little more than items in a tabular listing. Space permits no more here. They are fully reported and described in a voluminous technical literature, of which the industry as a whole may well be proud. And it is to be emphasized that not all these developments have sprung full grown from our temples of research. Indeed many of them reflect rather the practical inventiveness of the operating engineer than the disciplined research of the pure scientist. But in its broad and pragmatic sense it is just this cooperative interplay between the laboratory and field practice, which is the essence of worth-while industrial research. It is out of the mutual stimulation of the practicing engineer and laboratory scientist that have developed these important advances in the petroleum engineering profession.

And Now the Future

What of the future? While with respect to details, the prediction of specific results of research would be nothing less than astrological chicanery, the trends of broad emphasis of future research can be readily discerned. In view of the previously indicated major objective of production research it is to be expected that effort will be largely devoted to those aspects of production which offer promise of maximum increase in either cost reduction or oil recovery. These lie primarily in improving or modifying drilling operations and in lowering the residual oil left in the reservoir at the time of abandonment.

Several recent exceptions notwithstanding, it is highly probable that the exploitation of the remaining oil reserves in this country will require the drilling to increasingly greater depths — then, fifteen and twenty thousand feet — over the mainland, or at increasingly greater depths of water in offshore operations. It is not difficult to see, because of its approximately exponential increase with depth, that the mere cost of drilling and completion of oil wells can become the limiting barrier for developing our deep potential oil productive areas. Drilling represents an inescapable down payment for the recovery of the oil reserves. Yet, unless the rapidly increasing trend of this primary cash outlay is somehow arrested, the buyers' market for the fixed assets will be frozen out of the field of sound business enterprise.

Research on increased economy in drilling operations, improvements in current practices, or in the development of entirely new methods certainly should offer promise of tangible and valuable returns. Special emphasis on the latter approach has already crystallized through the medium of Drilling Research Inc., and no doubt much additional research effort in this field will be devoted in the industry in future years. In fact, successful research of this type may well be considered a *sine qua non* for insuring the very stability of the oil producing industry from a long term standpoint.

What of Recovery?

Of long-standing — as has been the problem of cheaper drilling — has been that of increasing the amount of economically recoverable oil. Much progress has been made in recent years in clarifying the factors which limit and control oil recovery. In essence these advances consist first in the recognition that under most conditions the water drive or gravity drainage producing mechanism will lead to maximum oil recovery, and secondly in understanding how these more efficient oil expulsion processes may be induced to control the recovery in par-

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ENGINEER'S FUTURE

Continued from Page 7

Proration got its initiation in 1926, both in East Texas and in Oklahoma. This gas question was still very much before the industry, and the Marlin Gas Committee had its first meeting in 1927. Out of that, H. C. Miller compiled the book, *The Function of Gas and Recovery of Petroleum.*

Petroleum Branch Formed

In 1923, the Petroleum Division of the AIME was formed. They had their first really technical meeting in 1925, in Casper, Wyoming; another in Tulsa, in 1926, and then in Fort Worth, in 1927.

At the same time, Seminole came in with gas lift, and that became quite prominent in California. Substantially all of those meetings were devoted to the technical side that had to do with recovery—devoted to problems of gas lift.

Now, there are two or three things that were quite evident up to that period of the development of production engineering. The first one was that gas is the primary thing, as far as recovery of petroleum is concerned. Water, as a recovery agent, was recommended by only a few, and certainly was recommended only as a nuisance, or as a troublemaker, as far as most of the petroleum industry was concerned.

The second thing is that up until that time, the well was the thing. This thing of looking at a reservoir as such, had not come before the industry at all, or before the technical men. It was what a well does, which was the entire problem, and not what happened in the reservoir.

That is quite surprising for a number of reasons. First, we recognized the necessity of offsets. We recognized and practiced both water flooding and gas injection. We were aware of the formation of gas escapes. And above all, the anticlinal theory was very much before everyone, which was an accumulation of oil or migration of oil—some said for long distances. And yet, as far as production was concerned, we looked only at the individual well.

Reservoir Pressure Unknown

The first recommendation that got into the reservoir idea was a paper by Moore in 1929, on the quantitative effect of gas-oil ratios, on the decline of average rock pressures. Notice that reservoir pressure was not before the industry. It was not a known term at that time.

That paper got relatively little recognition. The concept of a reservoir, as far as production engineering is concerned, didn't come before the industry until these Texas fields came in in 1932 or possibly it was in 1931. That brought a lot of things before us. First, we recognized it as a reservoir. We recognized it as a water reservoir and its importance and relative value to other sources of energy.

The next five years proved very remarkable and outstanding in the development of our technology of reservoirs.

So far, recovery problems and reservoir problems have been discussed primarily. There was, however, developing certain equipment, which was of no less importance. Not confined exclusively to this particular period but certainly coming within their primary development, if not initiated at that time, was mud control. The straight hole drilling, which was initiated in 1928, really got into practice during this period.

Coring had been known before, but it wasn't taken too seriously. Sidewall coring came in immediately following that period, as well as acidizing, and use of eight indicator drilling thermometers in determining a number of other conditions in the wells, etc. And certainly, above all, look at the impact of the results of geophysics on the increase in reserve during that period.

Now, back to the reservoir side of it. Bottom hole pressures first came in at that time. We knew something about porosity, but it was rather a laborious means of determining it. And it was during that period that practical means of determining porosity came into practice.

Permeability, at the beginning of this period, was a word which only a few of the engineers knew. Up until that time, porosity and permeability had been used interchangeably. And any time an engineer said permeability, somebody said, "What is that?" We soon found out what it was—or at least, found out something about what it was. I am not sure that we even know yet what permeability or porosity is, for that matter.

Fluid Properties Studied

The properties of reservoir fluids came in for intense study. It had been initiated three or four years before that. But it was still a technical curiosity—you might say, a laboratory thing—which had no other consideration.

The radial flow formula came into that, material valves, and the relative permeability. All of those things which we rely on today for all of our production engineering were either initiated, or really had their development, during the period of approximately five years.

Now, prior to this period, in the early 30's, the technical men were rather groping around, trying to find something. They were "lost babes in the woods." With the development of the East Texas field, and immediately following that, these other technical developments then began to get their fingers, first on this and then on that, but they didn't know what they had. They asked their research men and laboratory men and physicists as to what they had and what were the fundamentals. The physicists, the laboratory and research men took it seriously.

And did they come through? They gave us so many fundamentals, and are still giving us so many fundamentals, that most of the production engineers are so busy trying to find out what to do with their fundamentals, and applying them to such data, that they have almost forgotten to look upon what an oil well is.

I think it might be summed up in a a little quotation picked from a preface to a technical book published in the late 1920's. This sentence appears: "I do not dwell on hypothesis, for I take these to be unnecessary, in the light of our established laws of physics and mathematics." I sometimes wonder if our engineers aren't in exactly that position at the present time.

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Proposed for Membership

Total AIME membership on Sept. 30, 1949, was 15,988; in addition 4427 Student Associates were enrolled.

ADMISSIONS COMMITTEE

James L. Head, Chairman; Albert J. Phillips, Vice-Chairman; George B. Carless, T. B. Counselman, Ivan A. Given, Robert L. Hallett, Richard D. Mollison, and John Sherman.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend its privileges to every person to whom it can be of service but does not desire to admit persons unless they are qualified.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; AM, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

ALABAMA

Birmingham—Crowder, Robert Scott. (C/S—J-M). Giles, Claud Bryan. (M). Rankin, Frederick Voelker. (M).

ARIZONA

Aje—Cratty, Donald Robert. (C/S—J-M).
Phoenix—Henderson, Jesse Franklin, Jr. (M).

CALIFORNA

Fontana — Cherian, Thonipurackal-Varkkey. (J).
Fullerton—Ferguson, Cedric Keith. (J).
Laverne—McKee, Verona Isabelle. (M).
Oxnard—Stehle, Carl Vincent. (C/S—J-M).
Palos Verdes Estates—Field, Almeron Johnston. (J).
Santa Monica—MacLeod, Thomas Le Breton, Jr. (J).
Sonora—Stinson, Walter Allen, Jr. (C/S—J-M).
Sutter Creek — Buchanan, Edward. (C/S—S-M).

COLORADO

Denver—Conwell, Cleland Neeper. (C/S—J-M). Corbett, Robin James. (J).

CONNECTICUT

Bridgeport—Flores, Francisco Almeida. (M).

FLORIDA

Bartow—Ellis, Edward Jones. (M).

GEORGIA

Atlanta—Nees, John Morgan. (J).

ILLINOIS

Chicago—Parker, Howard Alfred. (R,C/S—J-M). Weymueller, Carl Robert. (C/S—S-J).
East Alton—Waters, Wade David. (R,C/S—S-M).
N. Riverside—Seery, Frank Edward. (M).
River Forest—Burnham, Charles Thomas. (J).
Riverside—Weir, John Paul. (C/S—S-J).
Rosiclare—Bailie, Harold Emerson. (M).

KANSAS

Garnett—Austin, Kenneth Olney. (C/S—S-J).
Hutchinson—Blincoe, Edward Irvine. (C/S—S-J).

LOUISIANA

Iota—Risien, Harvey Vineyard. (C/S—S-J).
Morgan City—Wilson, Fred. (J).
Shreveport—Grage, Victor Parker. (C/S—J-M).

MASSACHUSETTS

Brighton—Collins, William Francis. (M).

MICHIGAN

Berkley—Olson, John Henry. (J).
Detroit—Nagler, Charles Arthur. (C/S—AM-M).
Willow Run—Rush, Adron Isaac. (J).

MINNESOTA

Duluth—Spencer, George Herbert, Jr. (M).
Mahtomedi—Collins, Robert C. (J).
St. Cloud—Brammer, Donald James. (C/S—S-J).

MISSOURI

Bonne Terre—Wolf, Edward Hugo. (M).

MONTANA

Butte—Helehan, Thomas Joseph. (AM).
Nye—Toepfer, Peter Herbert. (M).

NEW JERSEY

Metuchen—Haskell, Albert Adams, Jr. (R, C/S—S-M).
No. Plainfield—Howe, Herbert E. (C/S—J-M).
Rahway—Conard, Clarence Knight. (M).

NEW MEXICO

Carlsbad—Hicks, Charles Wilson. (C/S—J-M). Lydick, Robert Lee. (J). Wheeler, Jesse Everett. (M).

NEW YORK

Brooklyn—Van Hare, George Frederick, Jr. (J).
Chappaqua—Parks, Francis Newton. (C/S—J-M).
Crestwood—Giesler, Henry Joseph. (J).
Douglaston — Butterworth, Spencer Keeler. (AM).
New York—Cox, Charles Raymond. (M). Fuchs, Warren J. (J). Petrie, Henry Joseph. (C/S—S-J). Wills, Frank. (J).
Niagara Falls—Webb, James Willard. (M).
Port Henry—Sirola, William Matthew. (M).
Suffern—Ettinger, Wolfgang Gerhart. (J).
Tahawus—Wright, Samuel Irwin. (C/S—J-M).

OHIO

Berea—Carroll, Walter (R,C/S—AM-M).
Shadyside—Lang, Emmett Thomas. (J).
Shaker Heights—Kennedy, Ralph Grant, Jr. (M).

OKLAHOMA

Enid—Snyder, Lenard David. (M).
Oklahoma City—Dannenberg, Richard Martin,
Tulsa—Barberil, Efrain Emeterio. (R,C/S—S-J). Giles, Frank Stewart. (M).

OREGON

Portland—Belusko, Vincent E. (M).

PENNSYLVANIA

Bala-Cynwyd—Hanson, Ralph Clark. (M).
Bethlehem—Howells, Edgar Harris. (C/S—J-M).
Bradford—Eckert, Frank Earl, Jr. (C/S—S-J). Kleiner, Abraham. (C/S—S-J).
Center Valley—Sawitzke, Edward A. (C/S—J-M).
Devon—Wharton, Heyward Myers. (J).
Freeland—Goeppert, Albert Richard. (C/S—S-J).
Harrisburg — Pennington, Fred Alexander. (M).
Montoursville—Hoyt, Charles Dalburg. (C/S—S-J).
Nemacolin — Fitzwater, Marcellus M., Jr. (C/S—S-J).
Norristown—Giacobbe, John B. (M).
Oakmont—Brennecke, Margaret Ware. (M).
Palmerton—Stutz, George F. A. (M).
Pittsburgh — Lamm, Arnold Edward. (M). Little, Samuel Guy. (M). Phillips, William J. (AM). St. Vincent, Frank. (R,C/S—J-M). Snyder, Clifford H. (M). Toering, Albert J. (C/S—J-M).
Summit Hill—Crawford, David Jenkins. (R, C/S—S-M).

SOUTH DAKOTA

Rapid City—Carr, Barton Ward. (J).

TENNESSEE

Oak Ridge—Boyle, Edward J. (C/S—J-M).

TEXAS

Austin — Justen, John Joseph. (C/S—S-J). Khayan, Mihran. (C/S—S-J).
Beaumont—Welchon, James Kenneth. (J).
Beeville—Fightmaster, Robert Richard. (M).
Corpus Christi—Edison, James Elmer. (J).
Dallas—Alford, Joe Benge. (AM). Johnson, John Peyton. (M). Monteith, Edward Everett, Jr. (R,C/S—S-J). Williams, Nelson Wheat. (C/S—J-M). Wilson, Malcolm Earl, Jr. (C/S—S-J).
El Paso—Ward, Oscar Thurmond. (C/S—S-M).
Falfurrias — Litherland, James George, Jr. (J).
Fort Worth—Walker, James Donald. (M).
Gonzales—Allen, Paul Adolphus, Jr. (J).
Hebbronville—Thomas Henry Evans. (J).
Houston — Harris, Washington Irving, Jr. (J).
Levelland—Helm, Cyrus Vard. (J). McPhail, Malcolm Charles. (C/S—S-J).
III. (C/S—S-J).
Odessa—Deats, Hollis Wendell. (R,C/S—S-J). Kidd, Thomas Wayland. (J). Showen, Ellsworth Witt. (M).
Refugio—Tonkin, Robert George. (C/S—J-M).
San Antonio—Coates, George Hunter. (M).
Wink—Feeser, John Russell. (R,C/S—S-J).

UTAH

Salt Lake City—Staats, Fred. (M). Walters, George Wilmer. (R,C/S—AM-M).

VIRGINIA

Big Stone Gap—Smith, William Clifford. (M).
Blacksburg—Bennett, Allen Vaden. (J).

WASHINGTON

Spokane—Fergin, George Stanley. (C/S—S-J).

WEST VIRGINIA

Beckley—Gates, Leslie Clifford. (M).
Huntington—Morrow, Oliver Perry. (AM).

WISCONSIN

Wausau—Smith, Robert Lewis. (C/S—S-J).

WYOMING

Superior—Barry, Jack C. (J).

ALASKA

Anchorage—O'Shea, John Joseph. (M). Saarela, Leo Hjalmar. (R,C/S—J-M).

ONTARIO

Copper Cliff—Lee, James Edwin. (C/S—J-M).
Islington—Wilson, James T. (AM).
Niagara Falls—Montgomery, Harold Reginald. (C/S—J-M).
Ottawa—Hume, George Sherwood. (M).
Toronto—Bell, Eric Charles. (J).
Virginiatown—Yule, Samuel Cameron. (M).

QUEBEC

Montreal—Dempster, William Eric. (R,C/S—S-J).
Mont Joli—Fairlie, Bertram Murray. (C/S—J-M).

SONORA

Estacion Morene—Llamas, Raymondo. (J).

CHILE

Chuquicamata — Parsons, Edward Wilson. (C/S—AM-M).

ECUADOR

Guayaquil—Fitzsimmons, Worth Martin. (R, C/S—J-M).

VENEZUELA

Caracas—Gorham, Edwin Lombard, Jr. (M). Moir, James Thomas, Jr. (M).

ENGLAND

Birmingham — Casewell, Edward William George. (C/S—JFA-M).
Chester—Wilson, Robert William. (J).

IRAQ

Basrah—Buckingham, Clifford Lewis. (C/S—J-M).

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AIME Board of Directors Meets Seven Hours At Annual Meeting—Reviews Many Problems

Seven hours were spent on AIME business by the Board of Directors at the Annual Meeting, and many important matters were reviewed. Twenty of the 26 elected Directors were present at the Sunday meeting, which began at 10 a.m. and wound up shortly after 5 p.m., with an hour out for lunch. Section delegates and Directors-elect were also on hand, as were seven of the ten Division Chairmen, who are Directors ex officio. President Lewis E. Young presided. Monday afternoon the incoming Board of Directors met in executive session immediately following the annual business meeting of the Institute, with President D. H. McLaughlin in the chair.

1949 Treasurer's Report

A few pertinent figures from the Treasurer's report for 1949, with comparable data in parentheses for 1948, follow: Income from dues, $225,973 ($208,015); initiation fees, $16,888 ($14,562); advertising, $85,721 ($68,344); publication sales, $20,889 ($28,727); miscellaneous income, $4,069 ($9,064); total income, $393,133 ($328,711). Expenses for publications, $300,364 ($236,916); Institute expenses (rent, library, Local Sections, Divisions, Branches, meetings, Secretary's traveling, insurance, pension), $83,137 ($104,871); General Office expense (salaries not otherwise allocated, accounting, membership, telephone, stationery, postage, furniture, miscellaneous), $90,450 ($80,157); total expense, $473,951 ($424,862). The income figures do not include $8,769 ($11,493) in the form of contributions. The operating deficit for 1949 was thus $72,048, compared with $84,658 in 1948. Chairman Andrew Fletcher pointed out that the large increase in publications' expense was an investment in better magazines for AIME members, which in future years should bring in more advertising revenue. The preliminary budget for 1950, which Fletcher also offered, indicates a balance in income and expenses because of a substantial increase in income expected because of the rise in dues and a larger volume of advertising. This can be more accurately established when the final budget is adopted at the April meeting of the Board. The Petroleum Branch, in particular, outlined a plan whereby it might be possible to reduce printing costs and increase advertising income in 1950.

A Controller for the Institute, in the person of George I. Brigden, without salary, as recommended by the Executive and Finance Committees, was appointed to review Institute accounting procedures.

A report of the ECPD Committee on Professional Recognition, recommending that all of the Founder Societies adopt uniform grades of membership, was discussed, but in view of the work involved in reclassifying all present Institute members it was voted not to adopt the proposal.

Considerable discussion arose from a proposal from the Mineral Economics Division, offered by Elmer Pehrson, that the AIME policy on controversial matters, as printed on page 85 of the 1948 Directory, be considerably broadened. Various arguments for and against were offered. The matter was considered so important that action was postponed until the April meeting of the Board to give time for further study.

Self-Supporting Meetings

At a previous Board meeting it had been voted that all Institute, Divisional, and Branch meetings be self-supporting so far as the AIME treasury was concerned, the idea being that no part of a member's dues should be used to finance a meeting which he might not be able to attend. Definite rules for financing and apportioning the cost of such meetings were adopted by the Board at this meeting and copies will be sent to all those concerned.

The plight of young men who had been in World War II and had subsequently completed their education, but who could not become Junior Members because they had passed the 30-year age limit, was discussed by Head. He advocated granting them permission to be admitted as Junior Members for a period up to three years following granting of their Bachelor's degree, provided only they had not reached the age of 33. Notice was given of an appropriate change in the bylaws to permit this action.

Proposed Amendment

The Board of Directors, at its meeting on February 13, 1950, gave notice of a further amendment to Article I, Section 5, of the Bylaws to be voted on at the April meeting of the Board, as follows:

Substitute for the second and third sentences the following: He shall be not more than 30 years of age at the time of his application, and shall not remain a Junior Member beyond his 33rd birthday, except that the Board of Directors shall have the power to waive the age limitation in the case of veterans of World War II.

Edward L. Clark, State Geologist for Missouri, presented the essentials of a project now under way by the Engineers Joint Council Committee on National Water Policy, in which AIME participation was desired. The aim of the committee is to give engineering advice to a Presidential Commission that is studying the question. Some difference of opinion was expressed as to the advisability of participating in the work of this committee. Further, it was estimated that the cost to the AIME would be several hundred dollars. It was finally voted to defer action.

A desire to make the Board of Directors more truly representative of all geographical and professional interest groups, and to improve its functional efficiency, led to the appointment of a committee consisting of W. M. Peirce, chairman, E. R. Price and Lloyd E. Elkins, which reported at this meeting. It recommended that for the

time being the number of elected Directors continue at 27, with the Divisional Chairmen Directors ex officio. It further recommended that the Nominating Committee be reduced from 19 to 18. Three of these would be appointed by the President, as in the past. Eleven of the remainder would be chosen by the Council of Section Delegates. Of the other four, two would be chosen by the Mining Branch, and one each by the Metals and Petroleum Branches. Heretofore, the Local Sections have named all members of the Nominating Committee except the three selected by the President.

Of the 27 elected Directors, the Committee felt that the President and past Presidents should not be considered as representing any geographical district, leaving 24. Further, it was believed desirable that the Nominating Committee each year have three Directorships (for a three-year term) at its disposal which are not preempted by fixed apportionment. This leaves fifteen. Of this number, it felt that six should be residents of the New York metropolitan district in order that they can be readily available for the day-to-day work of the Institute, and so that a good representation of Directors may be had at New York Board meetings. Of the remaining nine, it was recommended that one should come from each of the nine other geographical districts, which have been delimited to secure an approximate equal number of members in each. The Local Sections included in these districts are as follows:

1. New York.
2. Boston, Connecticut, Pennsylvania Anthracite, Lehigh Valley, Philadelphia.
3. Washington, D. C., Southeast, Florida, St. Louis.
4. Pittsburgh, Cleveland, Ohio Valley, Central Appalachian.
5. Chicago, Detroit, Upper Peninsula, Minnesota.
6. Colorado, Wyoming, Utah, Montana, Black Hills.
7. San Francisco, Nevada, Oregon, Columbia, North Pacific.
8. Southern California.
9. Arizona, Southwestern New Mexico, El Paso Metals, Carlsbad Potash, Permian Basin, Southwest Texas, Gulf Coast.
10. Kansas, Tri-State, Mid-Continent, Oklahoma City, North Texas, East Texas, Delta.

When a vacancy in the directorate exists from any of these districts, a nomination will be made by a committee consisting of the Chairmen of the Local Sections. It is suggested that they offer a choice of two men, of different Branch interests.

The Committee also suggested that in 1951 the Nominating Committee name not only a President but also a President-elect, and that thereafter only a President-elect be named each year, who would thus have at least one year of service on the Board before becoming President.

The Committee's plan was adopted and the Secretary was directed to draw up the necessary changes in the by-laws to make it effective.

Distribution was authorized to all new Junior Members of the Petroleum Branch of the Robert E. Hardwicke volume on "Antitrust Laws et al vs. Unit Operation of Oil and Gas Pools" through the courtesy of the Seeley W. Mudd Fund. The translation of "Bergwerk- und Probierbuchlein" was added to the list of volumes from which new Junior Members might choose as an added Mudd Fund gift volume. A second edition of "Basic Open Hearth Steelmaking," to be sponsored by the Fund, was also authorized.

1950 Directory

Plans for the 1950 Directory of AIME members were discussed. Instead of printing the Directory from the master file cards at Institute headquarters as formerly, postal cards were to be sent to all members about March 1, asking them to supply up-to-date information for printing in the Directory. These cards, when returned, will be sent direct to the printer. If cards are not returned, the titles and addresses on record at the Institute will be used instead. Much of the material in the first 115 pages of the 1948 Directory will be omitted, as will the listing of Student Associates.

The Board referred to the Council of Section Delegates the suggestion of the Gillson Committee on Democratization that a grievance committee be appointed to hear all members' complaints, seek out their cause, and do something about their rectification. Subsequently the Council decided that the hearing of grievances was a matter that it might itself assume, and each delegate was asked to be the clearing house for grievances emanating from members in his own local area.

On the day preceding the Board meeting the Council of Section Delegates had an all-day meeting, as a result of which certain matters were brought to the attention of the Board: (1) The Council voted to change its bylaws so that an alternate would have the privilege of voting, provided the Local Section from which he came certified to the Secretary of the Council three weeks prior to the meeting the selection of such alternate. The change was approved. (2) The Council asked for information on the reapportionment of Directors to geographical districts. The Board regarded that this had been answered in the report of the Peirce Committee. (3) A reduction in the initiation fee was recommended in the case of Junior Members applying for change in status to Associate Member or Member. It was suggested that one dollar per year of dues-paying membership be credited, up to a limit of $10. This was referred to the Admissions and Finance Committees for study and report to the Board. (4) The Council suggested that a committee be formed from the most influential members of the Institute to approach heads of companies from whom advertising in the Institute's journals might be secured. This aroused a great deal of discussion, which brought out the need for additional funds if all of the technical papers of merit presented to the Institute are to be published. A transcript of the discussion will be prepared for the Finance Committee to study.

The Council commended the Institute staff for the excellence of the three new journals, and President Young for his excellent and indefatigable services to the Institute during his term of office.

Following are the new officers of the Council of Section Delegates: Gerald M. Cover, Cleveland Section, chairman; M. I. Signer, Colorado Section, vice-chairman; T. B. Counselman, New York Section, secretary; Jack M. Shepherd, East Texas Section, L. M. Scofield, Minnesota Section, F. W. Strandberg, Montana Section, and F. T.

Moyer, Washington, D. C., Section, executive committeemen.

AIME participation in the sponsorship of an International Metal Congress in Chicago in October had been questioned by a member, and the matter was brought before the Board for discussion. Efforts had been made by the principal sponsor of the National Metal Congress to expand it into an international affair by using ECA funds to bring a group of European engineers and metallurgists to this country. Following discussion at the Board meetings on February 12 and 13, and at the meeting of the Institute of Metals Division Executive Committee, the decision was that sponsorship of such a congress, using public funds, was outside of the established policy of the Institute, but that if a foreign group should be invited to this country, as proposed, they would be welcome to attend any open meetings of the AIME Institute of Metals Division at the Chicago meeting.

Bylaws of the Minerals Beneficiation Division were amended to provide for a symposium committee, and to require securing acceptance of nominations from the nominee. Bylaws of the new Florida Section were approved, as were changes in the bylaws of several other Sections.

Raul de la Pena informally presented an invitation for the AIME to join with the GSA and the SEG in holding a meeting in Mexico City in 1951, and an invitation was presented by the Boston Section to hold the Annual Meeting of the AIME in Boston in 1953. Action was deferred in each case, the Board expressing its appreciation of the invitations.

Officers and Directors Elected at Executive Session

At the executive session of the Board, held at 5 p.m. February 13, C. V. Millikan was elected vice-president to succeed D. H. McLaughlin for a one-year term ending in February, 1951; Earle E. Schumacher was elected a Director for a one-year term ending in 1951; and Hjalmar W. Johnson was elected a Director for a two-year term ending in February, 1952 to succeed William E. Brewster, deceased. Andrew Fletcher was re-elected Treasurer, and Edward H. Robie Secretary, each for a one-year term. The following were named on the Executive Committee: D. H. McLaughlin, chairman; Earle E. Schumacher, vice-chairman; Philip Kraft, E. C. Meagher, and W. M. Peirce. The following comprise the Finance Committee: Erle V. Daveler, chairman; A. B. Kinzel and Gail F. Moulton.

The following dates for meetings of the Board and the Executive and Finance Committees were approved:

March 15, Executive and Finance Committee, New York

April 21, Board, New York

May 17, Executive and Finance Committee, New York

June 21, Board, New York

July 19, Executive and Finance Committee, New York

August 16, Executive and Finance Committee, New York

August 29 or 30, Board, Salt Lake City

September 20, Executive and Finance Committee, New York

October 18, Executive and Finance Committee, New York

November 15, Board, New York

December 20, Executive and Finance Committee, New York

January 17, 1951, Executive and Finance Committee, New York

February 18, Board, St. Louis.

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Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 601 Continental Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened, and no fees are involved.

Replies to the position coded Y-3284 and personnel coded M-511 and M-512 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

PERSONNEL

♦ Senior petroleum engineering student, University of California, 24, married; desires summer employment to gain field experience beginning June 19, 1950. Will travel. Code 128.

♦ Physicist, M.A. Expert on analogue computing applied to the hydrodynamics of reservoirs (electrical reservoir behavior analyzer); desires new connection, preferably in the development of bigger and better computing machines. Code 129.

♦ Petroleum engineer, assistant professor at a major university, desires summer employment June 1 to September 15. Experience in secondary recovery, production research, reservoir engineering and valuation. Code 130.

♦ Senior refinery engineer, graduate M.E. and E.E., registered in Texas, thoroughly experienced modern operations and utilities, process control and development, construction, erection. Available for development or engineering department. Foreign or domestic location. M-511.

♦ Petroleum geologist, 37, married, one child, B.S. degree geology. Experience includes 4 years' petroleum exploration, Peru, Ecuador, 2 Years' U.S.G.S., 2 years' Panama Canal. Desires permanent geological position in West, preferably Rocky Mountain region. M-512.

POSITIONS

♦ Senior petroleum production engineer, graduate with about five years' experience in oil and gas reservoir engineering. Knowledge of production technology research. Will make comprehensive studies of oil and gas reservoirs and determine the most efficient control and production method for maximum recovery. Cooperate in the recommendation of the design and operation of all production equipment. Coordinate production practice with laboratory research. Make recommendations on possible research problems. Recommend on locations of wells and methods of well completions. Location, Saudi Arabia. Y-3284. ★ ★ ★

MANAGEMENT'S FUTURE

Continued from Page 7

this is one man's view. Rather than try to suggest troublesome specific problems which may have been overlooked, I hope to point out some things that production technology is not doing now.

It may be felt that some of these are not the province of production technology. But are they? Management, except for strictly informative material, often finds oral and written communications from production technologists, which are long, yet indefinite or inadequate, in their conclusions or recommendations.

Authoritative Intuition

Alternative courses of action may be omitted, or they may be simply listed without a recommendation for adoption of one or the other, for the reasons shown. This assumes that busy and perhaps distant management will exercise what Morris Muskat terms authoritative intuition. But if the competent technologist near the source, and in a position to know and analyze all the background does not carry the matter as far toward proper decision as possible, what else can result?

Another item is this: Too often reports will excuse avoidable assumptions or postulations, because necessary measurements and data are not available. But despite organizational arrangements, production technology must surely bear part of the responsibility to see that reasonable measurements and records of drilling and production performance are always available.

Production technology sometimes fails to state the dollar angles completely, even in specific recommendations. Too often we see vague statements like: "This should reduce lifting costs." We still find too many reports neglecting obvious dollar angles of critical importance.

For example, a report with specific recommendations for installations of salt water disposal system caused by compliance with local laws neglected to review the reserve and relate its cost on a unit basis. Subsequent investigation showed that this particular lease would probably not pay out the added installation, and the property was subsequently sold.

What of the Future?

Now, what should production technology do in the future? In addition to continuing its excellent work, without which our industry's program cannot be maintained, it must also accept wider responsibilities. It must find time and means for creating understanding of such matters as proper spacing, unitization, production rates, etc., not only among us, but among lessees, legislators, regulatory bodies, and even the citizenry at large.

Who can do this better than those who work in production technology themselves? Conversely, it must point out those improper uses of technology, where it alone cannot guarantee proper results in the wrong legal or economic structure. For example, allocation of oil on MER's does not in itself assure the equity or real conservation, which its use may imply.

Production technology may indeed show how to recover an additional 10,000,000 barrels of oil through secondary recovery, under today's prices, costs and conditions. If, however, extreme taxes or a maladjusted supply-demand situation threatens the industry's stability, why should we not do what we can as individuals to act in these unfamiliar, but vitally related fields?

A state legislator once asked, "How can we tax the oil industry to get better conservation?" In other words, how can we promote conservation through more intelligent taxation? Who can answer that better than production technology?

Sights Should Be Raised

Production technology should look beyond the consuming technical goal, and as a proved group of thinkers and doers, engage actively in any and all community or individual activities which will maintain and build the kind of state, country and world we want — one that we need, where beneficial technology can continue its indispensable part.

Production technology should be the first to see and correct incorrect or misleading statements, such as the President's recent utterances on the Point Four program, for example. President Truman said, in connection with the Point Four program, which you all know is for the development of underdeveloped sections of the world: "I stand in my office and look at a globe. I see immense undeveloped rivers and valleys all over the world that would make TVA and Columbia Valley developments. I see untold resources. All it needs is somebody who knows the technical approach." Let me repeat that: "All it needs is somebody who knows the technical approach."

We know that production technology itself cannot accomplish the entire job alone. Indeed, we find nuclear scientists first to proclaim that we can neither stop nor control the destructive march of the greatest of all sciences now directed toward the uses of weapons.

Having tried to express what management feels production technology is doing today, a few things, perhaps, that it is not doing — or doing not too well — and finally, stating some things I think it should do in the future, I believe that we have a duty beyond the technical field itself to do what we can individually and en masse to insure an environment, however, where technology can continue its beneficial progress for the good of all men everywhere.

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EAST TEXAS SECTION

Continued from Page 19

The first article on well spacing was written by W. W. Cutler, Jr., appearing in the Bureau of Mines Bulletin No. 228. Cutler attempted to analyze the relationship of well spacing versus recovery of crude oil from a reservoir. Keller and Callaway devote their paper to pointing out that Cutler was in error "on all points needed to prove his beliefs."

It was pointed out during the discussion which followed Callaway's presentation that unitized fields provide an excellent opportunity in which to determine the optimum spacing pattern before drilling as discussed in the paper. Questions were raised in regard to the effects of pay thickness, permeability, and viscosity on the recoveries on different spacings.

Prior to Callaway's talk, Section Chairman Phil J. Lehnhard announced that present plans are to commence the proposed study group sessions with the first regular section meeting in the fall.

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New Policies Discussed By Branch Executive Committee in Day Long New York Session

THE allotment of one full day for the open meeting of the Branch Executive Committee at the recent Annual Meeting in New York opened the way for consideration of several important matters that are before the Branch at this time. Most previous meetings of the Committee have been limited to one-half day, and there has usually been a rush to get through the agenda. Incoming Branch Chairman John E. Sherborne presided.

Several important reports were the first items covered. Chairman Sherborne reported on the committee appointments for the Branch during the ensuing year, starting first with the nominating committee. Headed by retiring Branch Chairman Lloyd E. Elkins, as is customary, the committee consists of E. R. Brownscombe of Atlantic Refining Co. in Dallas, Fred Nelson of Texas Gulf Sulphur Co. in Houston, John Thacher of Standard Oil of California in Los Angeles, and W. B. Berwald of Ohio Oil Co. in Findlay. Sherborne reported next on the chairmen and vice-chairmen of the other Branch committees for 1950, and these are shown on page 3 of this issue of PETROLEUM TECHNOLOGY.

The next report was on the membership increase during 1949. The essential facts of this report are given in the news story on membership on the following page. Next the Treasurer's report was presented, which includes an analysis of the status of the Branch Special Projects Fund. This report was given in full on pages 14 and 15 of the March PETROLEUM TECHNOLOGY. Following this was a report on the appointments of Joe B. Alford as secretary and Jess E. Adkins as editor which were reviewed in the February and March issues of PETROLEUM TECHNOLOGY.

Next on the agenda was a report on plans for promoting the sale of advertising in PETROLEUM TECHNOLOGY, and this brought forth a discussion lasting almost two hours. When the magazine was established in Dallas no sales organization was set up immediately in order to see what developed in this field. Then, in late 1949, the firm of McDonald-Thompson, publishers' representatives on the West Coast, were employed as a sales agency to cover that part of the country. In order to make the magazine fully self supporting from advertising a sales organization on a nation-wide basis must now be established, and the Committee considered alternative plans to accomplish this. Essentially these plans are: (1) To employ an advertising manager and staff, (2) to employ publisher's representatives, and (3) to contract with a commercial publishing firm. No decision was made at this meeting, and as the plans are now incomplete, a report on what action is taken will be withheld until a later issue of the PETROLEUM TECHNOLOGY.

Publication of Statistical and Technical Material

Secretary Alford reported on the plans for inclusion of the annual *Statistics* volume in PETROLEUM TECHNOLOGY during 1950. A varitype machine has been acquired and Mrs. Barbara Bohl has joined the staff as operator. When the statistical data is reported by members of the Production Review Committee, it will be transposed to a form designed for the purpose, photographed, and then printed with offset printing methods on the standard page size of the magazine. A statistical section will be included from May through December, which permits the membership to receive the material more rapidly than heretofore. At the end of the year bound copies of all of the reports will be available for those who ordered them for 1950. This method of printing and distribution of the material will save several thousand dollars during the year.

The present procedure for selection of technical papers calls for the initial selection to be made by the Auxiliary Publications Committee of the Petroleum Branch, headed this year by Owen Thornton of The Texas Co. Those selected are then submitted to the Technical Publications Committee for the entire AIME for approval and assignment of a technical paper number. During 1949 some conflicts arose over this procedure and over the selection of some specific papers. Certain proposals were made by the Auxiliary Committee in order to iron out these difficulties, and Gail F. Moulton reported on the present status of the matter. The report indicated some of the conflicts had been resolved, and further changes would have to be authorized by the AIME board of directors.

Financial Assistance to Chapters and Sections

Since the establishment of the Branch office in Dallas in 1946, several Branch Chapters and Local Sections have requested financial assistance from the Branch to help with the development of mailing lists, etc. These requests had been met in the past by specific action of the Chairman and Executive Committee, but no definite policy had been established pertaining to such requests for financial assistance. The matter was discussed at length at this meeting, with part of the discussion going off at a tangent on the possibility of forming "functional" sections within geographical sections of the Institute. There was considerable agreement to the effect that this might be accomplished in the near future, and the matter will be considered carefully in several quarters of the Institute this year.

In establishing a policy on financial assistance, the Committed voted that a newly formed *Local Section* could apply for $100 upon its formation if: (1) it is predominantly petroleum in membership; (2) has never before received from AIME or a parent Local Section an amount in excess of $100, and (3) no part of the money is to be spent on food, drink or entertainment. For assistance to *Local Section Study*

Groups, the Committee retained a policy established in 1947 of granting $50 to these groups upon request for help on mailing and stenographic costs. No definite policy on assistance to Petroleum Branch Chapters was made because of the intricate relationships between these chapters and the Branch, but requests from the chapters will be considered individually while the matter is being given special study by the Executive Committee.

Another financial matter that came up for considerable discussion is the practices now used by the Branch and by Local Sections to finance social functions at meetings. For the Branch meetings particularly, funds are solicited from oil companies and service companies, and there has been some evidence in the past that this practice could lead to ill-will toward AIME. The discussion centered around other possible methods of financing these meetings, but no policy was established.

Electrical Logging Volume

The Seeley W. Mudd Fund, established in 1929 by the family of Colonel Mudd, sponsors the "AIME Series" of books which have been distributed free to Junior Members of the Institute in the past. Money is available now for the publication of a volume on petroleum to be given to Petroleum Branch Junior Members when they join. In late 1949 William H. Strang proposed that a volume of about 500 pages on "Electrical Logging" be published for this purpose, and circulated the proposal to several persons interested in the field of electrical logging. The proposed volume would be a collection of previously published papers on electrical logging, and the general reaction to the proposal was that such a volume would be very helpful to junior engineers, but that far more could be accomplished by revising these papers to eliminate overlap and contradictions and to alter observations and conclusions on the basis of present knowledge. This would entail the task of writing such a book.

An alternate proposal made was the idea of collecting two or three fundamental papers on a number of subjects in a volume to be given to Junior Members. Discussion from the Committee and members attending centered around these proposals, but no decision was reached for lack of information on which to proceed. A special committee will be appointed to study the matter and recommend what action should be taken. It is expected that some sort of a volume will be published for Junior Members as the money is available for this purpose from the Mudd Fund.

Fall Meetings in 1951 and 1952

The Oklahoma City Section extended an invitation to the Petroleum Branch to hold its Fall Meeting there in October, 1951. Henry Waszkowski, Section chairman, extended this invitation and presented a letter from the Oklahoma City Chamber of Commerce confirming his inivitation. On the basis of these invitations, Oklahoma City was definitely selected for the Fall Meeting in 1941.

E. L. Petree, chairman of the Gulf Coast Section in Houston, extended an invitation of that group, confirmed by the mayor of Houston, for the Branch to meet there in the Fall of 1952. This invitation was accepted on a tentative basis, and tentative plans are being made to meet in Houston in October, 1952.

To conclude the meeting, the Committee acted on several miscellaneous matters. The complete transcript of the meeting is available in the Dallas Office for anyone who desires to see it.

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BRANCH LEADS INSTITUTE IN MEMBERSHIP

By providing 571, or 35 per cent, of the 1618 new members admitted to the Institute during 1949, the Petroleum Branch extended its five-year supremacy as the fastest growing major technical group within the AIME. At year's end total AIME membership was at a new high of 16,315 members and 4,952 student associates for a total of 21,267. In the Petroleum Branch, 3,502 members had paid their dues by the end of 1949, which represented 22.9 per cent of the money from dues received by the Institute.

Under the leadership of Frank Briggs, chairman of the membership committee for 1949, the Branch conducted a membership campaign which had good results. A post card was sent to members, asking for the names of potential members, and about 950 names were reported to the Branch Office. A complimentary copy of the August and September issues of PETROLEUM TECHNOLOGY, with an explanatory note appended, was sent to each person reported as a potential member. By the end of February, 1950, approximately 60 of the 950 who received magazines had applied for membership. The applications for membership averaged 48 for each month during 1949, but the number jumped to 80 for October. The complimentary copies of the magazine, plus the incentive provided by the Branch Fall Meeting in October probably accounted for this increase.

The number of junior members declined slightly and stood at 23.9 per cent of the AIME total at year's end. The decrease was caused by the fact that under the new bylaws, junior members cannot be more than 30 years of age at the time of election (instead of 33) and because of the fact that the war interrupted the usual flow of students into the profession. The further requirement, beginning in 1950, that no one can continue as a junior member after his 33rd birthday will also act to temporarily restrict the number of junior members.

Petroleum Branch membership in mid-year 1944 was 1,940, or 15.9 per cent of the AIME. Growth since then has been as follows:

Year	New Members in Petroleum Branch	Per Cent of AIME New Members
1944	279	19.5
1945	274	21.1
1946	462	27.0
1947	458	30.9
1948	504	29.0
1949	571	35.0

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RESEARCH'S FUTURE

Continued from Page 31

ticular fields. Yet, even under most favorable circumstances such operations will leave unrecovered at least 20 to 30 per cent of the original oil content. Such ultimate losses are conveniently written off by referring to them as "unrecoverable, short of mining." But this defensive and fatalistic philosophy cannot forever imprison the imagination of the research scientist.

The writer does not pretend to see through the heavy fog of plausible impossibilities enveloping the present area of practicability — if he did, he would probably be at this moment consulting his patent counsel. But he does feel that the future will find research leaders trying out and exploring many ideas seeking to lower the limit of that oil which must remain "unrecoverable, short of mining." When it is realized that each per cent reduction in this irreducible limit would increase the world's present recoverable reserves by more than 1,000,000,000 barrels, it will be clear that the stakes are high enough to justify many questionable research gambles. Indeed the driving motto of the production research man of the future may well be: "Recover the Unrecoverable." ★ ★ ★

ENGINEER'S FUTURE

Continued from Page 32

What of the future? As valuable as the physics and mathematics may be in the study of reservoirs, what we need to do is get acquainted with oil wells.

Now, an oil pool has just as much character as a nation of people. The individual wells within that particular pool have just as much character as the individuals within a nation. We are going to have to learn what that character is. Perhaps we have their reputation at the present time, but what we need to know is their character.

Kipling got pretty close to character in one of his poems on the ladies, when he said: "There are times when you think they might, and there are times when you know that they might, but the things you will learn from the yellow and the brown, will help you sleep with the white."

We have gone out to these oil wells, and slept with them. That is one way of finding out their character, or at least something. We have got to learn about those wells, and their performance by something which can't be measured with a micrometer, or a slide rule.

We have asked the researchers for fundamentals. They are still producing. We haven't asked them for anything but fundamentals. Let us get out and become acquainted with the oil wells, and I see no other reason why the physicists, the laboratories, and the other research workers can't give us just as much information on the character of those wells as they have given us on fundamentals, and when we learn the characters we will be making real progress in production engineering. ★

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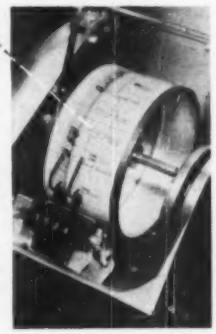

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Book Reviews

Petroleum Engineering

Vol. 45, number 3B of the Quarterly of the Colorado School of Mines, Golden, Colorado, 1950. 51 pp., illus., paper, $.50.

The publication contains the papers delivered at the Conference on Petroleum Engineering held at the Colorado School of Mines September 30 and October 1, 1949. Included are "Gas-Condensate Fields" by W. E. Brown; "The Valuation of Oil Properties for Secondary Recovery" by R. C. Earlougher; "Secondary Recovery of Petroleum" by Paul D. Torrey; "Petroleum Conservation and Conservation Laws" by D. V. Carter. This book is a part of the Seventy-Fifth Anniversary Volume entitled "Mineral Resources in World Affairs," which will reprint all the papers presented and much of the discussion at the conferences on the occasion of the Seventy-fifth Anniversary of the School.

Earth Waves

By L. Don Leet. John Wiley & Sons, Inc., and the Harvard University Press, New York, 1950, $3.

This book is Monograph No. 2 in the Harvard Monographs in Applied Science, a series of books reporting the results of university research. A compact summary of present knowledge of waves of the earth, the monograph discusses their application and use in prospecting for minerals, studying hurricanes, measuring vibrations from dynamite blasts to determine their effects on buildings, and mapping broad earth structures of geologic interest. Results of recent research on types of wave motion, interpretations of refraction profiles, and microseisms are also presented.

1949 ASTM Standards on Petroleum Products and Lubricants

Prepared by ASTM Committee D-2 on Petroleum Products and Lubricants. American Society for Testing Materials, Philadelphia. 750 pp., heavy paper cover, $5.50; cloth cover, $6.15.

The latest (November, 1949) compilation of American Society for Testing Materials Standards on Petroleum Products and Lubricants brings together in compact, readily usable form, most of the ASTM standards, test methods, and specifications widely used in this field.

Prepared by ASTM Committee D-2 on Petroleum Products and Lubricants, the edition gives in their latest form 120 ASTM standards, including 102 test methods, 12 specifications, two lists of definitions relating to petroleum and rheological properties of matter, two tentative recommended practices for the purchase of uninhibited mineral oil for use in transformers and in oil circuit breakers, and for designating significant places in specified limiting values; and other material.

Covered are motor and aviation fuels; diesel and burner fuels, kerosene and illuminating oils; lubricating oils, greases, petrolatums and paraffin waxes, plant spray oils and petroleum sulfonates, cutting fluids, electrical insulating oils, light hydrocarbons, hydrocarbon solvents, crude petroleum, thermometers, and miscellaneous.

ELEMENTS OF THE PETROLEUM INDUSTRY

A third printing of *Elements of the Petroleum Industry*, edited by E. DeGolyer, originally published 10 years ago, sponsored by the Seeley W. Mudd Memorial Fund, is now available. The price is $2.50 to members of the AIME, including Student Associates, and $5 to others. A new edition has been authorized, but its preparation has not yet begun.

AIME TRANSACTIONS VOLUMES

All Transactions Volumes authorized for 1948 and 1949 publication are now available except Vol. 182, on Nonferrous Smelting and Refining, which should be published shortly, and Vol. 179, Petroleum Division, which is now out of print. Copies have been sent to all those on our records as having ordered these volumes; others may place orders at $3 for paid-up members, $6 for non-members (domestic) and $6.50 (foreign).

The recent volumes include:

175. Institute of Metals (924 p.)
176. Iron and Steel (552 p.)
177. Coal (594 p.)
178. Mining Geology (556 p.)
179. Petroleum Development and Technology (395 p.)
180. Institute of Metals (713 p.)
181. Metal Mining, Industrial Minerals, Mineral Industry Education, and Geophysics. (Rocky Mountain Fund volume). (472 p.)
182. Nonferrous Smelting and Refining (330 p.) (available shortly).
183. Minerals Beneficiation (Gemmell Memorial Fund volume). (372 p.)

Transactions volumes in the new size, 8½ by 11½ in., covering all Transactions material published in the three journals in 1949, are now being issued. Vol. 186, Petroleum Development and Technology (332 p.) is already available. Soon to be issued are: Vol. 184, Mining Branch, and Vol. 185, Metals Branch. The price is $3.50 for a first copy to members, $7 to nonmembers in the United States, and $7.50 to nonmembers in foreign countries.

"Statistics of Oil and Gas Production," with data for 1948 (524 p.) was published last fall. It was supplied free to members who received the Journal of Petroleum Technology. To other members the price is $3, and to nonmembers $6 domestic and $6.50 foreign. Similar data for 1949 will be included in the Journal of Petroleum Technology during 1950, and a bound volume of this same material will be available at the end of 1950 or early in 1951.

Author's Guide

John Wiley and Sons, Inc., New York, 1950, a rewritten version of Wiley's The Manuscript: A Guide for Its Preparation, $2.

A completely rewritten version of Wiley's "The Manuscript: A Guide for Its Preparation," the new volume is a start-to-finish manual on the most efficient methods of handling manuscript, illustrations, and proof. It shows the technical author how his manuscript progresses through principal stages on its way to publication, acquainting him with the functions of several hundred skilled and experienced workers required to bring his work to the printed page.

Additional information is included on formal publication and copyright, preparing for reprinting, revisions and new editions, and on details of editorial style. The end papers of the book contain a table of do's and don'ts which every prospective author will find valuable.

In preparing "Author's Guide," the publishers hope to enlist the cooperation of technical authors before their manuscripts are prepared. ★ ★ ★

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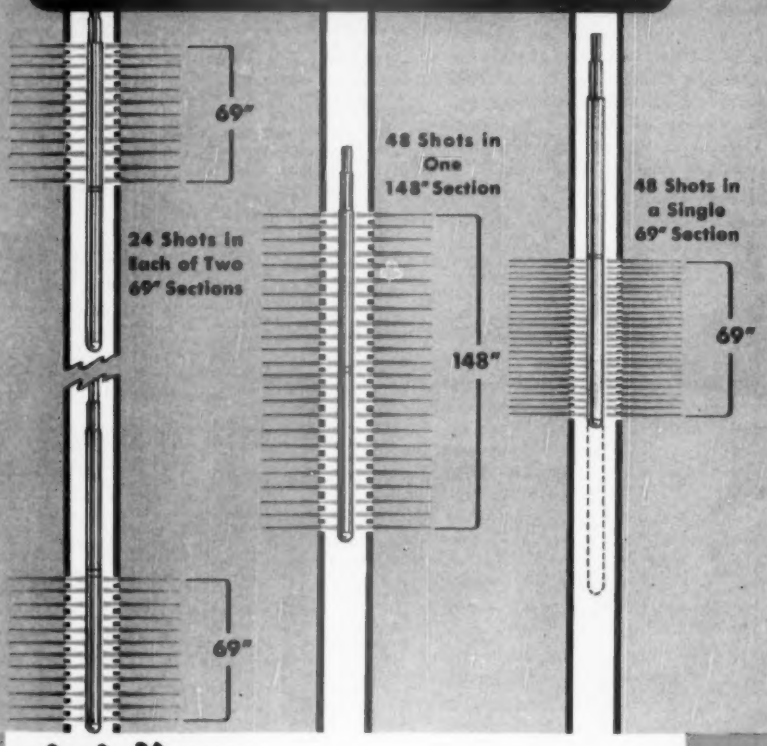

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DISCUSSION OF THIS AND ALL FOLLOWING TECHNICAL PAPERS IS INVITED

Discussion in writing (3 copies) may be sent to the Editor, *Journal of Petroleum Technology*, 601 Continental Building, Dallas 1, Texas, and will be considered for publication in the Transactions volume *Petroleum Development and Technology*. Discussion will close December 1, 1950. Any discussion offered thereafter should be in the form of a new paper.

THE ESTIMATION OF PERMEABILITY AND RESERVOIR PRESSURE FROM BOTTOM HOLE PRESSURE BUILD-UP CHARACTERISTICS

C. C. MILLER, MEMBER AIME, **A. B. DYES** AND **C. A. HUTCHINSON, JR.,** JUNIOR MEMBER AIME, THE ATLANTIC REFINING CO., DALLAS

ABSTRACT

This paper presents a simple and practical method for the estimation of effective permeability and reservoir pressures from the rise in bottom hole pressure when a well is shut in. The equations on which the method is based consider a stabilized well producing from a uniform formation when flow is shut off at the sand face followed by the unsteady state flow of a compressible liquid from regions far from a well to points closer in during the build-up period. An approximation for extending the method for two-phase flow in the reservoir is also presented.

In order to compare the effects of extremes in the conditions existing at the external boundary of the reservoir, two general equations defining the build-up characteristics of the reservoir are shown: first, for a reservoir with constant pressure maintained at the radius of drainage, and second, for a reservoir with no influx over the radius of drainage. These equations define the build-up characteristics for the shut-in well as functions of time, the permeability and porosity of the drainage area, the viscosity and compressibility of the fluid flowing, the production rate prior to shut-in, and the radius of drainage of the well.

When a well is shut in at the surface, rather than at the sand face, flow will continue into the well bore after shut-in due to the compressibility of the fluids in the bore. The effect upon the build-up characteristics of this flow into the well after shut-in has been studied by means of the electrical analyzer. From the basic relationships and consideration of the limitations due to continued flow after shut-in, methods have been developed for the estimation of the effective permeability of an area from the plot of the build-up characteristics of the well producing that area. Likewise, equations are presented for the estimation of the reservoir pressure from an early portion of the build-up curve.

By means of the electrical analyzer, studies have been made concerning the variations in the build-up characteristics resulting from damaged or improved permeability in the immediate vicinity of the well bore. These studies show that the permeability estimated from the build-up curves represents the average effective permeability of the majority of the drainage area and that the permeability in the immediate vicinity of the well does not affect this estimate. Since the major portion of the drawdown is in the immediate vicinity of the well, variations in the permeability of this area greatly affect the productivity of the well as expressed by the productivity index. From pressure build-up and productivity index tests the ratio of the permeability of some arbitrarily specified area immediately surrounding the well and the effective permeability in the majority of the drainage area can be computed. This ratio is a measure of any damage to the well incurred in drilling or reworking and likewise any benefits as a result of remedial measures.

In build-up tests and many other tests that are made on a producing well it is at least desirable, if not absolutely necessary, that the well be stabilized prior to testing. A method is presented here for relating the time required to stabilize a well and the reservoir and fluid properties. An equation is also presented for approximation of the length of shut-in time required to obtain sufficient build-up data for the estimation of permeability and reservoir pressure.

[1] Reference given at end of paper.

Manuscript received at the office of the Petroleum Branch October 1, 1949. Paper presented at the Petroleum Branch meeting in San Antonio, Texas, October 5-7, 1949.

INTRODUCTION

The estimation of the effective permeability and of the reservoir pressure around a well has long been a problem for the petroleum engineer. Permeabilities were first estimated from direct analysis of the cores taken from the well and later supplemented by productivity index data. These methods, however, do not permit determination of the actual permeability of the formation in that the conditions in and around the well bore at the time of coring or testing cause considerable deviation from the actual values. It has been pointed out by many authors[1,2,3,4] that the rate of build-up in a shut-in well is affected by the permeability of the producing formation. It may be reasoned, therefore, that the build-up pressure tests should be valuable for a direct estimation of the effective permeability based on actual performance of a well. This is especially true since the build-up characteristics of a well are dependent upon the permeability in the majority of the area of drainage and not upon the permeability in the immediate vicinity of the well.

In order to secure valuable information from material balance studies of a reservoir, reliable reservoir pressure data are essential. These data are frequently obtained by shutting in the wells and allowing the pressure to build up and approach reservoir pressure. It is a familiar practice to shut in a well and after a fixed period of time record a bottom hole pressure measurement which is taken to represent the actual reservoir pressure. This, of course, is an erroneous assumption, for only in fields of very high permeability will the equilibrium reservoir pressure be recorded, and it is therefore inadequate to measure the reservoir pressure in this manner, especially in those tight formations where the rate of build-up is comparatively slow. Thus, several methods have been devised for the estimation of the reservoir pressure. These methods are dependent upon the build-up characteristics of the well. Among the contributions to the estimation of reservoir pressure from field data are the methods presented by Muskat[1] involving a semilogarithmic plot of the build-up characteristics and by Arps and Smith[2] employing a rectilinear plot of the rate of build-up. Included in these methods are the assumptions of an incompressible fluid which flows from the reservoir into an open flow string increasing the back pressure on the formation. A more fundamental approach to the problem has been presented by Muskat in which he considers a compressible fluid in a radial flow system with the pressure at the external boundary maintained constant.[5] The present paper gives further consideration to this method and includes a consideration of the effect of varying degree of migration over the radius of drainage as well as a consideration of the effect on the build-up curves of varying the permeability in the immediate vicinity of the well.

It is the object of this paper to present a simple method for the estimation of the effective permeability and reservoir pressure from the rise in bottom hole pressure when a producing well is shut in. A second objective is to show that build-up and productivity tests furnish complementary information for evaluating the degree of damage or improvement to the permeability in the area of the reservoir immediately surrounding the well bore. An illustrative example follows the discussion to assist in application of the method.

BUILD-UP EQUATIONS

The equations defining the build-up characteristics for a well shut in at the sand face and producing from a uniform formation containing a homogeneous compressible liquid with a steady state distribution prior to shut-in are[6,5]

$$\bar{\Delta p} = \ln \bar{r}_e - 2 \sum_{n=1}^{\infty} \frac{e^{-x_n^2 \bar{t}}}{(x_n)^2 \, J_1^2 \, (x_n)} \qquad (1)$$

for a radial drainage area with constant pressure maintained at the external boundary and

$$\bar{\Delta p} = \ln \bar{r}_e - \frac{3}{4} + \frac{\pi^2}{2} \sum_{n=1}^{\infty} \frac{J_1^2(x_n) U^2(x_n)}{J_1^2(\bar{r}_e x_n) - J_1^2(x_n)} e^{-\bar{r}_e x_n^2 \bar{t}} \qquad (2)$$

for a radial drainage area with zero influx over the external boundary. In this later case a steady condition exists, referred to here also as a steady state, in which pressure gradients throughout the reservoir remain constant while the pressure throughout the reservoir is uniformly declining.

The dimensionless variables $\bar{\Delta p}$ and $\bar{t}$ are defined by the equations

$$\bar{\Delta p} = \frac{0.001127 \; 2\pi kh \, (p - p_f)}{Q \mu F} \qquad (3)$$

and

$$\bar{t} = \frac{0.0002637 \; kt}{f c \mu r_e^2} \qquad (4)$$

* See Appendix for derivations.

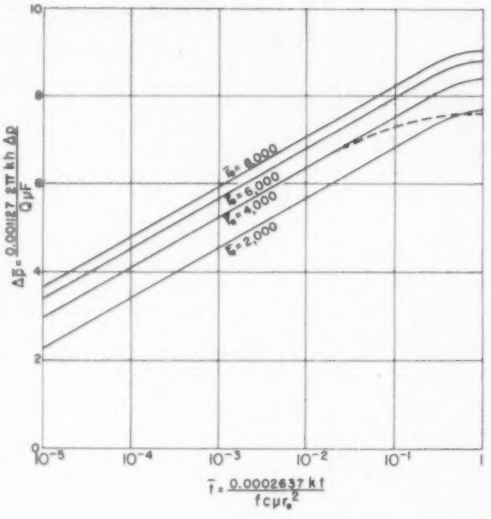

FIG. 1 — CALCULATED RISE IN BOTTOM HOLE PRESSURE IN A SHUT-IN WELL. STEADY STATE PRESSURE DISTRIBUTION OBTAINED PRIOR TO SHUT-IN BY CONSTANT PRODUCTION RATE. SOLID LINES FOR RESERVOIR WITH CONSTANT PRESSURE MAINTAINED AT THE RADIUS OF DRAINAGE. DASHED LINE FOR CLOSED RESERVOIR WITH NO INFLUX OVER RADIUS OF DRAINAGE AND $\bar{r}_e = 4{,}000$.

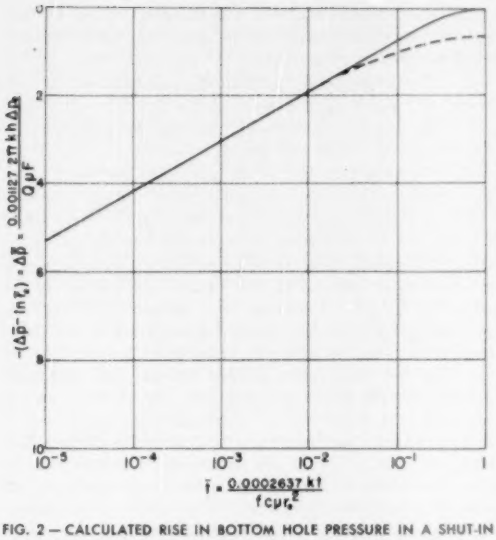

FIG. 2 — CALCULATED RISE IN BOTTOM HOLE PRESSURE IN A SHUT-IN WELL. STEADY STATE PRESSURE DISTRIBUTION OBTAINED PRIOR TO SHUT-IN BY CONSTANT PRODUCTION RATE. SOLID LINE FOR DRAINAGE AREA WITH CONSTANT PRESSURE MAINTAINED AT THE RADIUS OF DRAINAGE. DASHED LINE FOR CLOSED AREA WITH NO INFLUX OVER THE RADIUS OF DRAINAGE.

where

k = effective oil permeability, md
h = effective pay thickness, ft
Q = production rate prior to shut-in, STB/Day
μ = oil viscosity, cp
F = formation volume factor, $\frac{\text{Res bbl}}{\text{STB}}$
f = total porosity, fraction
c = mean liquid compressibility, psi^{-1}
r_e = radius of drainage, ft
pf = bottom hole flowing pressure at time of shut-in, psi
p = bottom hole pressure during build-up, psi, and
t = time, hours.

A numerical evaluation of equation (1) is presented in Table I. Values of $\bar{r}_e$ of 2000, 4000, 6000, and 8000 are used which correspond to 18, 72, 162, and 288-acre well spacings respectively for $r_w = 1/4$. The evaluation of equation (2) for $\bar{r}_e = 4000$, corresponding to a 72-acre well spacing and $r_w = 1/4$ is presented in Table II. The numerical values presented in Tables I and II are also presented in graphical form plotted as $\Delta\bar{p}$ vs. log $\bar{t}$ in Fig. 1 and $\Delta\bar{p} - \ln \bar{r}_e$ vs. log $\bar{t}$ in Fig. 2.

It may be seen in Fig. 2 that the early part of the build-up is independent of the conditions existing at the radius of drainage since the curves for the build-up in an area with constant pressure maintained at the external boundary and for the build-up with no influx over the external boundary coincide in this early section.

PERMEABILITY FROM THE BUILD-UP CURVE

Examination of Fig. 1 shows that the build-up characteristics plotted with dimensionless variables, $\Delta\bar{p}$ and log $\bar{t}$, appears to be a straight line in the sections of $\bar{t} = 10^{-5}$ to approximately $\bar{t} = 10^{-1}$. This apparently straight section of the curve is not actually a straight line as might be determined by proper differentiation of either equations (1) or (2). However, this section of the curve is sufficiently straight for practical purposes. The straight line sections of the build-up curves in Fig. 1 are parallel as is indicated by the fact that the curves become coincident upon translation by the quantity ln $\bar{r}_e$ as shown in Fig. 2. Though only one actual numerical evaluation of equation (2) has been calculated, additional curves also covering the range of $\bar{r}_e = 2000$-8000 were obtained on the electrical analyzer[2] which resulted in coincident curves when translated by the quantity ln $\bar{r}_e$. The slope of these lines may be taken as 1.147. This slope is important in that it relates the permeability and the slope of the straight line section of the build-up curve (when pressure is plotted vs. log time instead of vs. time) according to the relation

$$\frac{\Delta(\Delta\bar{p})}{\Delta(\log t)} = \frac{\frac{kh}{141.2Q\mu F}\Delta(\Delta p)}{\Delta(\log t)} = 1.147 \quad . \quad (5)$$

Rearranging this equation the permeability, k, may be shown as a function of the slope, m, of the straight line section of the pressure-log time build-up curve as

$$k = \frac{162.5\ Q\mu F}{mh} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The semilogarithmic plot of a field build-up test will generally show the straight line section as indicated for use in equation (6) for permeability estimation. However, an earlier

Table I

Build-Up Characteristics for a Shut-In Well in a Drainage Area Having Constant Pressure Maintained at the External Boundary in a Radial Flow System Well Produced at Constant Rate Prior to Shut-In to Attain Steady State

$\bar{t}$	$\Delta\bar{p}$ $\bar{r}_e = 2000$	$\bar{r}_e = 4000$	$\bar{r}_e = 6000$	$\bar{r}_e = 8000$
10^{-5}	2.261	2.954	3.360	3.647
10^{-4}	3.401	4.094	4.500	4.787
2×10^{-4}	3.7743	4.4674	4.8729	5.1606
5×10^{-4}	4.2045	4.89865	5.30411	5.59180
10^{-3}	4.55070	5.24485	5.65031	5.93800
2×10^{-3}	4.89250	5.58665	5.99211	6.27980
5×10^{-3}	5.35590	6.04905	6.45451	6.74220
10^{-2}	5.70280	6.38595	6.80141	7.08910
2×10^{-2}	6.04944	6.74259	7.14805	7.43574
5×10^{-2}	6.50744	7.20069	7.60615	7.89384
10^{-1}	6.85404	7.54817	7.95263	8.24032
2×10^{-1}	7.19597	7.88912	8.29458	8.58227
5×10^{-1}	7.52970	8.22285	8.62830	8.91600
1	7.59695	8.29010	8.69556	8.98325

Table II

Build-Up Characteristics for a Shut-In Well in a Drainage Area with No Fluid Migration Over the External Boundary in a Radial Flow System

Well Produced at Constant Rate Prior to Shut-In to Attain Steady State

$\bar{t}$	$\Delta\bar{p}$ $\bar{r}_e = 4000$
6.25×10^{-4}	5.02
1.25×10^{-3}	5.354
3.125×10^{-3}	5.808277
6.25×10^{-3}	6.148454
1.25×10^{-2}	6.482556
3.125×10^{-2}	6.903227
6.25×10^{-2}	7.187298
1.25×10^{-1}	7.409087
3.125×10^{-1}	7.535509
6.25×10^{-1}	7.543964

apparent straight line section which is not accounted for by the build-up equations may be evident in this plot. The earlier straight line section will have a greater slope than that to be used in the permeability equation. In an attempt to discern the cause of this variation from the calculated build-up curve, possible deviations from the conditions specified in the derivations of the equations for the build-up relations were examined, and it was found that the most obvious deviation was the fact that the build-up relations were derived for a well shut in at the sand face. In actual field build-up testing the well is closed in at the surface and there is flow into the well after shut-in due to the compressibility of the fluids in the well bore. This flow into the well after shut-in will be at a rate equal to the production rate prior to shut-in at the start of the test and will drop to zero as the pressure is finally built up. Several methods were tried in an attempt to find an analytical solution for the build-up relations considering this declining rate of flow into the well after shut-in. However, because of the complexity of analytically describing changes occurring in the well bore a complete study of the effects was not made. The electrical analyzer[5] was used to illustrate these possible effects and their magnitudes on the build-up curves. Studies with the electrical analyzer were conducted such that the well was drawn down for a constant production rate to produce a steady state prior to shut-in. A constant pressure was maintained at the external boundary. Upon attainment of the steady state distribution, the well was shut in and the build-up measured as a function of time. It was found that for a well shut in at the botton the electrical analyzer produced a curve matching the calculated curve as obtained from equation (1). In the section of the build-up plot from $\bar{t} = 10^{-2}$ to 10^{-1} the analyzer curve and calculated build-up curve coincided precisely. However, in the section $\bar{t} = 10^{-4}$ to $\bar{t} = 10^{-3}$ slightly lower values were observed in the analyzer curve. This may be attributed to insufficient subdivision of the close in portion of the reservoir in the analyzer. The deviation, however, was insufficient to invalidate the use of the analyzer for these experiments. This problem might be attacked by the LaPlace Transformation methods of Hurst and Van Everdingen.[12] However, the authors have not investigated this possibility since the electrical analyzer was available.

In order to obtain the build-up characteristics of the well in the case where there is flow into the well bore after shut-in, it was necessary to simulate the well bore in the electrical analyzer. This was accomplished by means of the addition of capacitors at the well end of the reservoir. These capacitors were contained in an expansion unit such that the capacitance could be varied as the pressure at the bottom of the well varied. Of course, as oil flowed into the well after shut-in the average compressibility of the bore fluid decreased, necessitating a decrease in the electrical capacitance of the well bore unit of the analyzer. The capacitance of the bore was computed from the pressure-volume curve of the reservoir fluid. Two situations were considered for this type of test. The first case considered flow into the well bore after shut-in with the well containing only gas prior to shut-in. Although such a situation of only gas in the bore prior to shut-in will never actually exist in an oil well, this condition was studied as the large gas compressibility would cause a maximum deviation from the curve for a well shut in at the sand face. A 10,000-ft well drilled on a 72-acre spacing (1000-ft radius) was chosen for this study. The second case considered a 10,000-ft well bore filled with gas and oil prior to shut-in. Approximately 45 per cent of the bore volume was occuped by undissolved gas prior to shut-in for this test. The two curves that were produced from these tests of flow into the well bore after shut-in under the conditions just cited are shown plotted with dimensionless variable $\Delta\bar{p}$ and $\bar{t}$ in Fig. 3.

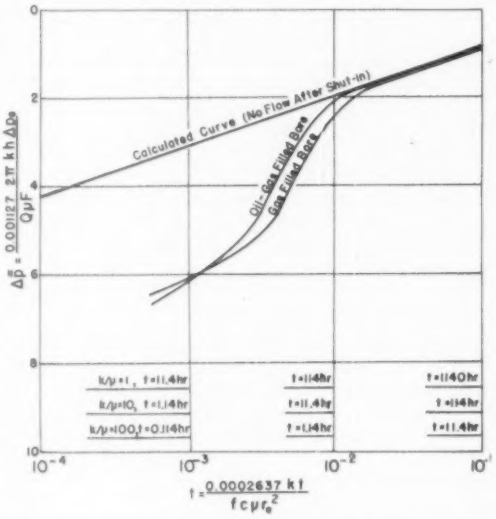

FIG. 3 — THE EFFECT OF FLOW INTO THE WELL AFTER SHUT-IN ON THE BUILD-UP CURVE.
OIL AND GAS FILLED WELL BORE 10,000-FT WELL.
GAS FILLED WELL BORE 10,000-FT WELL.
CALCULATED CURVE FROM EQUATION (3). TIMES GIVEN FOR K/μ VALUES ABOVE FOR SYSTEM $f = 0.2$, $c = 1.3 \times 10^{-6}$ psi^{-1}, AND $\bar{r}_e = 4{,}000$.

The calculated curve for the range of build-up considered is also included in Fig. 3 to provide a means for comparison. It will be noted that the flow into the well after shut-in causes a delaying action in the build-up as might be expected. However, after a comparatively short period of time a rapid build-up occurs and the curve becomes parallel if not practically coincident with the calculated curve assuming no flow into the well after shut-in. It will also be noted that an earlier straight line section which deviates from the calculated curve is present in these electrical analyzer build-up curves as had been expected. This is in direct correspondence with the earlier straight line section that is obtained in actual field build-up test curves.

The development for the equations for the build-up relations has considered that a uniform permeability exists in the reservoir. This situation, however, is not true and its effect has been considered by means of further electrical analyzer comparisons. It may justifiably be assumed that in the immediate vicinity of the well bore there may be a damaged or improved permeability area caused by the drilling procedures or treatment. The electrical analyzer was used to determine the effect on the build-up characteristics of such a damaged or improved area in the immediate vicinity of the well. This was accomplished by changing the resistance around the well in the analyzer, which change would depict a change in permeability immediately around the well. The radius of drainage of the well studied on the analyzer was 1000 ft. For the illustration of this effect the permeability to a radius of 23 ft from the well was changed to represent a twofold and a fivefold increase and a decrease to 1/2 and 1/5. A constant drawdown was maintained for these tests, so necessarily the production rates for these runs varied where there was a change in permeability. Pressure build-up curves obtained in these tests are shown plotted with dimensionless variables in Fig. 4. The dimensionless variable proportional to pressure, $\Delta\bar{p}$, is defined by the equation

$$\Delta\bar{p} = \frac{0.001127\ 2\pi kh}{FQ\mu}\ (p_e - p) \quad . \ . \ . \ . \quad (7)$$

where k is the permeability of the majority of the reservoir and not that of the damaged or improved area in the immediate vicinity of the well and p_e is the pressure at the radius of drainage at shut-in. These curves show that the effects of this damage or improvement are very rapidly eliminated in the build-up and that the curves soon coincide with the calculated curve. It may be noted at this point in the case where either increase or decrease in the permeability is exhibited in the immediate vicinity of the well the drawndown will be greatly different from the drawdown that would be exhibited in the same reservoir with a constant permeability throughout the drainage area. Thus, the permeability that is calculated from the slope of the straight line section of the build-up curve represents the actual effective permeability in the majority of the drainage area of the reservoir and is not affected by high or low permeability sections in the immediate vicinity of the well. This fact suggests a method for evaluating the conditions in the immediate vicinity of the well. This type evaluation will be discussed later.

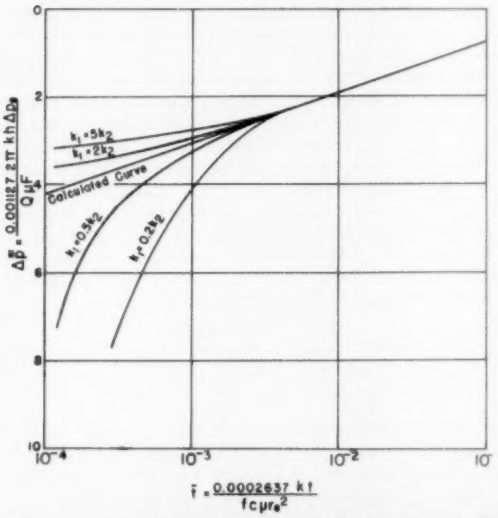

FIG. 4 — THE EFFECT OF A DECREASED OR INCREASED PERMEABILITY IN THE AREA IN THE VICINITY OF THE WELL ON THE BUILD-UP CURVE WELL SHUT IN AT THE SAND FACE. $\bar{r}_e = 4{,}000$. EXTENT OF k_1 TO $\bar{r} = 92$

The analysis of the effects on the build-up curve caused by existing conditions different from those assumed for the derivations of the equations should be continued to include the conditions where both local variation in permeability and flow into the well bore after shut-in exists. This problem was also treated by means of the electrical analyzer considering a 10,000-ft well filled with gas and oil prior to shut-in and including local permeability variations used in the previous tests. The results of these tests are shown plotted with dimensionless variables in Fig. 5. It may be seen in these curves, as in the curves for the tests considering damage or improvement and flow into the well bore after shut-in separately, that the curve approaches a condition where it is parallel to the calculated curve for a well shut in at the sand face and with uniform permeability throughout the drainage area. This would indicate that the section of the straight line that is parallel to the calculated curve may be used for permeability determination without error. However, much of the straight line section of the curve has been masked by the effects of flow into the well bore after shut-in, and it is necessary to make an opportune choice of the section of the curve that is to be employed in the permeability equation, since only a small portion of the total curve may be parallel to the calculated straight line section.

In order to develop a method to determine that the proper portion of actual field build-up test curve has been used in permeability determination, it is necessary to consider the calculated curve. The upper limit of the straight line section (Fig. 1) is approximately $\bar{t} = 2 \times 10^{-1}$ for a reservoir with constant pressure maintained at the radius of drainage and $\bar{t} = 3 \times 10^{-2}$ for a closed reservoir. A possible check of the upper limit of the straight line section of the actual field build-up test curve is suggested by this fact and may be accomplished by checking the upper limit of the actual field build-up plot for conformity with this upper limit of the straight line section of the calculated curve. In the calcula-

tion of $\bar{t}$ from equation (4) it is necessary to assume a value of r_e. If the well were stabilized prior to shut-in as required by equations (1) and (2) such that the pressure wave would have reached its maximum radius, the radius of drainage may be approximated from well spacing. If the final break in the field curve is included in the observed data (not an apparent break due to well bore effects), the calculated $\bar{t}$ for the last point of the straight line section should be of the order of 10^{-1}. Due to the long times required this final break is rarely obtained, in which case the last observed point usually gives a $\bar{t}$ falling in the range of 10^{-2} to 10^{-1}. If a straight line section is selected that is too early in the build-up curve and with too great a slope due to flow into the well after shut-in, the time as well as the permeability determined will be too low, giving a value well below the cited range.

NON-STABILIZED CONDITIONS

In actual practice there may be an additional deviation from the conditions assumed in the derivations for the build-up characteristic equations. This deviation arises from the fact that a considerable period of time is required for stabilization of the well to essentially steady state conditions prior to shut-in. However, the necessary steady state is sufficiently approximated in many cases to make the equations applicable. In the case of a well definitely unstabilized at the time of shut-in the analysis breaks down. The authors have found in such instances where the equations are not applicable that the electrical analyzer provides very satisfactory answers concerning the build-up characteristics and this method should be employed in such instances.

RESERVOIR PRESSURE FROM THE BUILD-UP CURVE

As pointed out before, many authors have examined the build-up characteristics to obtain methods for reservoir pressure estimation. However, the methods developed require that a considerable portion of the build-up curve be known before they are applicable. Also, flow into the well after shut-in and/or an increase or decrease in the permeability around the well cause erratic build-up curves and resulting erroneous estimation of reservoir pressure by the semilog plot of Muskat or the Cartesian rate plot of Arps and Smith.

The straight line section of the build-up curve corresponding to the straight line of the calculated curve in Fig. 1 may be used for reservoir pressure estimation in conjunction with the build-up equations. A measure of the reservoir or final build-up pressure around the well may be found in terms of the dimensionless $\Delta\bar{p}$ calculated for $\bar{t}$ increasing without limit. The final build-up, $\Delta\bar{p}_e$, for a reservoir with constant pressure maintained at the radius of drainage is given by the equation

$$\Delta\bar{p}_e = \ln \bar{r}_e \quad \ldots \quad (8)$$

For the reservoir with no influx across the external boundary the equation for $\Delta\bar{p}_e$ is

$$\Delta\bar{p}_e = \ln \bar{r}_e - \frac{3}{4} \quad \ldots \quad (9)$$

Considering the method of derivation of these equations, in effect this is a method of material balance for the determination of reservoir pressure. The resolution of these two equations for the determination of reservoir pressure requires that the flowing pressure prior to shut-in be known. However, that flowing pressure measured by the pressure bomb is not in direct correspondence with the flowing pressure as required by the equations. This condition exists because of the possible difference in permeability in the immediate vicinity of the well and the permeability in the rest of the drainage area. Let us consider that it is therefore necessary to determine a hypothetical flowing pressure for use in the determination of the reservoir pressure. This flowing pressure is the pressure that would exist at the bottom of the well for the production rate at the time of shut-in if the permeability around the well were the same as that determined from the build-up curve. The determination of the hypothetical flowing pressure that is to be used may be accomplished in the following manner: An r_e corresponding to the well spacing is assumed. Employing this r_e the straight line section of the field build-up curve may be matched with the straight line section of the calculated curve, from which may be determined the hypothetical flowing pressure according to the equation

$$p_f = p - \Delta p = p - \frac{\Delta\bar{p}\ FQ\mu}{0.001127\ 2\pi kh} \quad \ldots \quad (10)$$

where the pressure p is taken from the field plot and $\Delta\bar{p}$ is the dimensionless pressure variable taken from the calculated curve at a $\bar{t}$ corresponding to the time that the pressure p was observed. Having determined the hypothetical flowing pressure the reservoir pressure may then be calculated by means of the equation

$$p_e = p_f + \Delta p_e = p + (\Delta\bar{p}_e - \Delta\bar{p}) \frac{FQ\mu}{0.001127\ 2\pi kh} \quad \ldots \quad (11)$$

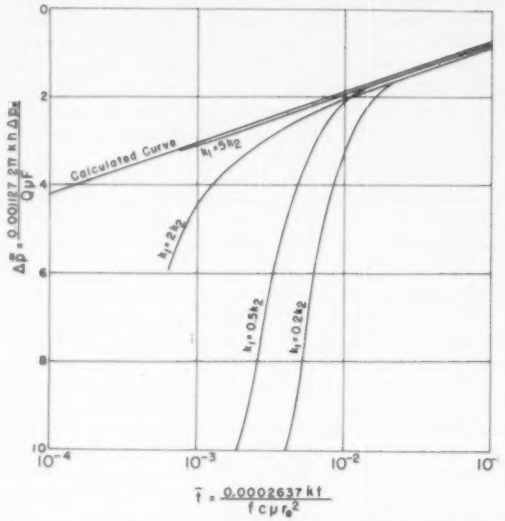

FIG. 5 — THE EFFECT OF FLOW INTO THE WELL BORE AFTER SHUT-IN AND A DECREASED OR INCREASED PERMEABILITY AROUND THE WELL ON THE BUILD-UP CURVE. $r_e = 4{,}000$. k_1 EXTENDS TO $r = 92$. OIL AND GAS FILLED BORE, 10,000-FT.

where $\Delta\bar{p}_s$ is calculated by equation (8) or (9), whichever is considered applicable. For wells with the drainage radius of approximately 250 ft to 1000 ft there is approximately a 10 per cent difference in the value of $\Delta\bar{p}_s$ as calculated from equations (8) and (9). It is necessary, therefore, to make an opportune choice of the equation to be employed for the determination of the reservoir pressure, and in such instances where neither is applicable some intermediate value may be chosen.

The chief point for error in this calculation is the assumption of the value of r_e which is usually done from well spacing. A 5 per cent error in the estimation of r_e leads to approximately a 1 per cent error in the theoretical drawdown, which in a high permeability formation means an error in the order of a few pounds. In a high pressure formation producing under open flow conditions where the drawndown is large this error may be in the order of 20 pounds.

BUILD-UP CURVES — TWO-PHASE FLOW

The relationships that have been presented to this point have considered the flow of a homogeneous compressible fluid through a porous medium. It would be of course advantageous to extend this method to include drainage areas in which both oil and gas were flowing. Considering that in the reservoir away from the well the pressure is fairly constant, the pressure functions μ_L, μ_g, F, ρ, and S may be assumed constant. Likewise, the saturation is fairly constant and the dependent variables k_{rg} and k_{rL} may also be assumed constant. These assumptions of essentially constant conditions have been reported to hold except for a very short transition period as the reservoir pressure falls below the saturation pressure of the oriignal reservoir fluid.[11] Applying these assumptions, Darcy's Law, and material balance considerations the build-up equations are shown to take the same form as for the single-phase flow case with a change in form of the dimensionless variables.* The resulting equation for effective oil permeability is the same as equation (6) where oil production rate and oil viscosity at approximately reservoir pressure are employed. The dimensionless variables $\Delta\bar{p}$ and $\bar{t}$ are defined by the equations

$$\Delta\bar{p} = \frac{0.001127\ 2\pi kh}{Q_L \mu_L F_L}\,\Delta p \qquad (12)$$

and

$$\bar{t} = \frac{0.0002637\ k}{fc_T \mu_L r_e^2}\left(\frac{\delta_L + \delta_g R}{F\delta_T}\right)t \qquad (13)$$

Equation (13) is used as equation (4) for checking the upper limit of the straight line section of the field build-up curve for conformity with a calculated curve. The same range of $\bar{t}$ applies. The total compressibility, C_T, is established at an estimated reservoir pressure as is the total density, δ_T. If the calculated pressure differs significantly from that estimated an adjustment may be necessary in these factors. In the authors' experience the quantity in parentheses has always been very nearly unity.

Table III

k/μ	t_s (days) 20 Acre Spacing	40 Acre Spacing	80 Acre Spacing	160 Acre Spacing
1	42	82	166	333
10	4.2	8.2	16.6	33.3
100	0.4	0.8	1.7	3.3

Time Required to Attain Steady State by Constant Production Rate (From equation (14). $C_L = 100\%$, F = 0.2, and $c = 1.5 \times 10^{-6}$ psi^{-1}).

* For derivations see Appendix.

TIME TO APPROACH STEADY STATE

The preceding equations have all been derived for a system with a steady state density or presure distribution prior to shut-in of the well. This distribution is obtained by flowing the well at a constant production rate for a sufficient period of time prior to shut-in. A graphical method[7] for the transient solution of the diffusivity equation provides a means for the determination of this time. In a finite time of course steady state will not actually be attained, but it will be approximated sufficiently for all practical purposes. Employing this method, the time required to approach steady state conditions for either assumed boundary condition is a function of the radius of drainage, permeability, and porosity of the formation, and compressibility and viscosity of the fluid. It is independent of the rate of production and the net thickness of the pay. For one-phase flow this relationship is[7]

$$t_s = \frac{fc\mu r_e^2}{k} \qquad (14)$$

where t_s is the time in days required to approximate a steady state. A similar equation for two-phase flow may be obtained by replacing $fc\mu/k$ by the factors of K', the modified diffusivity, obtaining

$$t_s = 50\,\frac{fc_T \mu_L r_e^2}{k\left(\frac{\delta_L + \delta_g R}{F\delta_T}\right)} \qquad (15)$$

where the values are obtained in the same manner as for equation (13). It will be noted that it is necessary to know the permeability in employing these equations. However, it is necessary to stabilize a well prior to a test before the permeability is known. In such instances the approximate time required to obtain a steady state distribution will be indicated by this equation if the range of permeability values that are expected is used in the equation. The initial pressure was assumed to be constant throughout the area for this derivation, and thus the time required for the steady state approximation represents the maximum period to be expected. Table III shows the range of time values that might be expected in single-phase flow. In such instances where the well has been produced for some time and it is desired to stabilize at a new production rate this time for the attainment of steady state at the new production rate will be less.

SHUT-IN TIME REQUIRED FOR PERMEABILITY DETERMINATION

Because it is undesirable to shut in a well over a long period of time, it is necessary in planning a pressure survey to estimate in advance the length of shut-in time required to obtain a sufficient section of the build-up curve for the determination of permeability. An expression for this time required may be derived directly from an examination of the calculated build-up relations as plotted in Fig. 2. This will give

a relationship for the time required to obtain a sufficient section of the build-up curve for permeability determination as a function of the porosity, compressibility, viscosity, radius of drainage and permeability that are being considered. Approximate knowledge of these factors will enable the engineer to more accurately estimate the length of time that is required to shut in the well. The upper limit of the straight line section of the build-up curve plotted as pressure versus logarithmic time is in the region of $\bar{t} = 5 \times 10^{-2}$. This will be true in all cases. Employing this value in equation (4) and solving for t we have for one-phase flow

$$t_{si} = \frac{190\ \phi c \mu r_e^2}{k} \qquad \ldots\ldots\ldots \quad (16)$$

where t_{si} is the time required in shut-in hours. This may be converted for two-phase flow in the same manner as equation (15). Table IV shows the range of time intervals that might be expected for single-phase flow. As in the case for the determination of the time required to approach steady state, it is necessary to know the value of the permeability prior to obtaining that value. It is necessary, therefore, to employ approximations of this permeability value with the answer of course resulting in an approximation of the time required to obtain a sufficient portion of the build-up curve for permeability determination. This equation though eliminates considerable uncertainty in the mind of the engineer requesting shut-in time of the well.

PERMEABILITY AROUND THE WELL

The permeability as determined by equation (6) from the slope of the build-up curve represents the effective permeability of the drainage area away from the well, as was indicated by the tests showing the changed permeability in the immediate vicinity of the well. The permeability as estimated from the productivity index using the steady state radial flow equation represents the average effective permeability of the entire drainage area. If these two permeabilities are different, there may exist a section in the immediate vicinity of the well with a permeability different from that of the majority of the area drained and their ratio is a measure of the degree of difference. This may be visualized more readily if an arbitrary radius of extent of the low or high permeability area around the well is taken. An equation relating these values is

$$\frac{k_r}{k_i} = \frac{\frac{k_r}{k} \log \bar{r}_r - \log \frac{\bar{r}_e}{\bar{r}_i}}{\log \bar{r}_i} \qquad \ldots\ldots \quad (17)$$

where r is the radial extent of the permeability in the immediate vicinity of the well, k_i the permeability in the immediate vicinity of the well, k_r the permeability way from the well estimated from the build-up curve, and k the average permeability estimated from productivity index. In shot wells $\frac{k_r}{k}$ may appear to be small enough to give a negative k_i. This, of course, can not exist and has been caused by arbitrarily assigning too small a value to r_i.

If the permeability determined from the slope of the build-up curve is greater than the permeability that would be determined from the productivity index, there is an indication of a damaged or low permeability area in the immediate vicinity of the well. Likewise, if the productivity index permeability is greater than that permeability as determined from the slope of the build-up curve, there will be an area of higher permeability around the well. This will enable the reservoir engineer to determine the presence of a damaged or improved permeability region at the sand face. The obvious place for application of this analysis is in the determination of the effects of drilling fluid on the permeability near the sand face. This indicates whether treatment should be recommended to improve the productivity of the well. The method may also be used for quantitative evaluation of treatment designed to improve the permeability in the immediate vicinity of the well.

Table IV

k/μ	t_{si} hours 20 Acre Spacing	40 Acre Spacing	80 Acre Spacing	160 Acre Spacing
1	167	315		
10	16.7	32	63	126
100	2	3.2	6.3	12.6

Shut-In Time Required to Obtain Sufficient Data for Permeability Determination From (16). $C_t = 100\%$, $F = 0.2$, and $c = 1.5 \times 10^{-5}$ psi^{-1}.

EXAMPLE ILLUSTRATING METHOD OF CALCULATION

In order to illustrate the method of procedure the following calculation is made for a typical well producing a tight formation. The build-up curve on this well, Well A, is shown plotted in Fig. 6. The following is a tabulation of the fluid and formation properties and flow information:

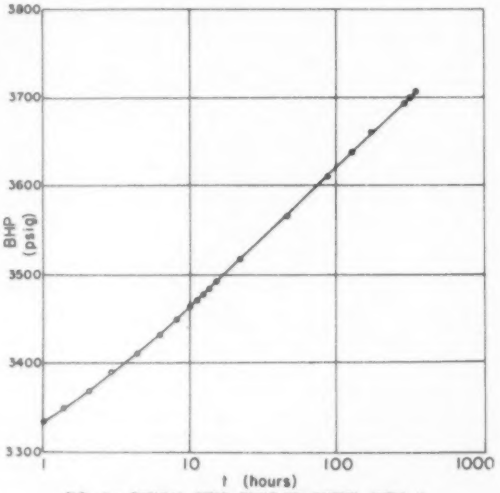

FIG. 6 — TYPICAL FIELD BUILD-UP CURVE, WELL A.

$PI = 0.183$ BOPD/psi
$Q = 115$ BOPD
$h = 120$ ft
$r_e = 1300$ ft
$f = 0.15$
$F = 1.69$
$c = 1.52 \times 10^{-6}$ psi^{-1}
$\mu = 0.33$ cup

There were wells producing from the same formation in the immediate vicinity of Well A, and thus this case approaches a closed drainage area with zero influx over the external boundary. An unsaturated oil is flowing in the formation.

The slope of the straight line section of the build-up curve, Fig. 6, is determined as

$$m = \frac{p_2 - p_1}{\log \frac{t_2}{t_1}} = \frac{3705 - 3495}{\log \frac{335}{17}} = 162$$

where p_2 and t_2 are the upper end of the straight line section and p_1 and t_1 the lower end.

To estimate the effective permeability this slope value is used in equation (6) and the permeability calculated as

$$k_e = \frac{162.5\ Q\mu F}{hm} = \frac{(162.5)\,(115)\,(0.33)\,(1.69)}{(120)\,(162)} = 0.537$$

At this point it is necessary to check that the slope of the proper section is used. This is done by calculation of the $\bar{t}$ for the upper end of the straight line section from equation (4)*

$$\bar{t} = \frac{0.0002637\ kt}{fc\mu r_e^2} = \frac{(0.0002637)\,(0.537)\,(335)}{(0.15)\,(1.52\times10^{-6})\,(0.33)\,(1300)^2} = 0.0374.$$

Since this value falls in the range of $\bar{t} = 10^{-2}$ to $\bar{t} = 10^{-1}$ the proper straight line section was used and the permeability estimation is valid.

For the estimation of reservoir pressure the value of $\Delta\bar{p}$ corresponding to the $\bar{t}$ just calculated and $\bar{r}_e = \frac{1300}{1/4} = 5200$ is obtained from Fig. 1 or Fig. 2.

$\bar{t} = 0.0374$ $\qquad$ $t = 335$

$\Delta\bar{p} = 7.30$ $\qquad$ $p = 3705$

The hypothetical flowing pressure is calculated from equation (10)* and $\Delta\bar{p} = 7.30$ as

$$p_f = p - \frac{\Delta\bar{p}\ Q\mu F}{0.001127\ 2\pi kh} = 3705 - \frac{(7.30)\,(115)\,(0.33)\,(1.69)}{(0.001127)\,(2\pi)\,(0.537)\,(120)}$$
$$= 2678 \text{ psig.}$$

The theoretical drawdown in terms of the dimensionless $\Delta\bar{p}$ is calculated from equation (9) since this case approaches a closed drainage area. Equation (8) would be used for constant pressure maintained at the radius of drainage. This $\Delta\bar{p}_e$ is calculated as

$$\Delta\bar{p} = \ln \bar{r}_e - \frac{3}{4} = \ln(5200) - \frac{3}{4} = 7.80$$

This dimensionless variable proportional to pressure may be converted to pressure, psi, and added to the flowing pressure to obtain reservoir pressure, or the reservoir pressure may be calculated directly from equation (11) as

$$p_e = p + (\Delta\bar{p}_e - \Delta\bar{p})\,\frac{Q\mu F}{0.001127\ 2\pi kh}$$
$$= 3705 + (7.80 - 7.30)\,\frac{(115)\,(0.33)\,(1.69)}{(0.001127)\,(2\pi)\,(0.537)\,(120)}$$
$$= 3775 \text{ psig.}$$

The over-all mean effective permeability of the drainage area may be calculated from the well-known radial flow equation as

$$k = \frac{PI\ \mu F \log \bar{r}_e}{0.00307\ h} = \frac{(0.183)\,(0.33)\,(1.69)\,(3.716)}{(0.00307)\,(120)} = 1.03 \text{ md.}$$

Since this is a higher permeability than that estimated from the build-up curve, it indicates that a high permeability exists in the immediate vicinity of the well. By use of equation (17) it may be estimated that to an arbitrary radius of 25 ft that $k_r \cong 9k_e$.

FIELD BUILD-UP ANALYSES

The authors have subjected approximately 80 build-up curves to the analysis described in this paper. From these 80 curves, seven sets of data have been chosen to illustrate a number of possible conditions existing in build-up testing. These curves are shown plotted with the dimensionless variables in Figs. 7, 8, and 9. The curves plotted in Fig. 7 are from wells which are producing a highly unsaturated formation and in which the well bore was mostly filled with oil prior to shut-in, and thus there was very little flow into the well bore after shut-in since the average compressibility of the well bore fluid was low. The curves shown in Fig. 8 are for wells also producing an unsaturated formation but with a drawdown to approximately saturation pressure such that considerable gas was in the well bore prior to shut-in, allowing an appreciable flow into the well bore after shut-in. The curve plotted in Fig. 9 is for a well producing a two-phase formation, and thus the average compressibility of the well bore fluid was high permitting appreciable flow after shut-in.

Considering first the build-up curves that are shown plotted in Fig. 7, it may be seen that these curves generally follow the type shown in Fig. 4 from the analyzer build-up studies which might be expected since there was little or no flow into the well bore after shut-in. Well A indicates a high permeability region in the immediate vicinity of the well, and thus the early section of the curve falls above the calculated values (not shown but essentially coincident with curve C). The value of $k_r = 5k_e$ has been estimated for a radius of extent of k_r to 25 ft. Well B indicates an extremely high permeability in the immediate vicinity of the well, and the calculations estimate an approach to infinite permeability around the well to a radius of 25 ft. Unlike Well A, Well B had been acidized in an attempt to improve the permeability in the immediate vicinity of the well. However, this should not be construed to constitute a value of acidization correlation since it is entirely possible that Well B was drilled into a very high permeability lens. To attempt to evaluate the improvement obtained from acidization it is necessary to have tests before and after treatment. The build-up test of Well C indicates a well with very little difference in the permeability

* For the two-phase flow of oil and gas in the drainage area equation (13) would be used in place of equation (4) and equations (10) and (11) altered for two-phase flow.

around the well and that away from the well, and thus the build-up curve is practically coincident with the calculated curve for a well producing a uniform formation. The build-up curve for a damaged well is shown by the build-up of Well D. It is known in this formation that most wells show a damaged condition. This may explain the finding that the permeability in the immediate vicinity of the well to a radius of 25 ft is one-fourth of the permeability in the majority of the drainage area away from the well. The point X marked on these curves corresponds to the point in Fig. 4 where the curves coincide with the calculated curve for the build-up of a well producing a uniform permeability zone. It will be noted that this is approximately the point of convergance of the curves shown in Fig. 7. However, it should not be expected that the curves of Fig. 7 correspond exactly to the curves shown in Fig. 4 in that there is some flow into the well after shut-in, which tends to result in lower values on the curves as may be seen by comparison of Fig. 4 and Fig. 5.

The curves shown in Fig. 8 are for build-up curves of a formation producing near the bubble point, and there is thus more flow into the well bore after shut-in than those curves just discussed. Well E represents a well producing from a relatively uniform permeability zone, while Well F represents a well producing a zone in which there is a low permeability region in the immediate vicinity of the well. Neither of these wells has been acidized. For the case of no flow into the well bore the point X again shows the point at which the effects of variation in permeability near the well are negligible. The point Y indicates the upper limit for the convergence of the analyzer curves where there is flow into the well bore after shut-in and increased or decreased permeability zones in the immediate vicinity of the well. It will be noted that in Fig. 8 the convergence of these curves with the theoretical curve occurs between the points X and Y as might be expected. The trends indicated in Fig. 8 are the same as those shown in Fig. 5. However, exact correlation should not be expected since the amount of flow after shut-in was different. The point Y does not indicate the maximum possible limit for convergence of the curves since a greater decreased in permeability around the well could exist and since gas accumulated in the immediate vicinity of the well would result in a material in that region with a compressibility higher than has been assumed. This additional compressibility may have an effect similar to flow into the well bore resulting in an even greater deviation from the calculated curve. However, for the 80 wells studied this value was not exceeded.

Fig. 9 shows the build-up curve of Well C producing an area containing both oil and gas. It will be noted in this curve that convergence with the calculated curve occurs near the point Y indicating appreciable flow after shut-in as would be expected for this type well.[7] The points X and Y have the same significance as in the preceding figures. Comparison of the permeability from the build-up curve and the permeability from the productivity index tests in which the reduction to effective permeability near the well due to gas accumulation has been included indicates that production is from a practically uniform permeability area.

In Figs. 7, 8, and 9 the build-up data had been chosen to represent a number of various cases similar to those studied by means of the electrical analyzer, the results of which are plotted in Figs. 3, 4, and 5. It will be noted that an earlier straight line section than the one to be used for permeability determination is frequently present in these field build-up curves and that these sections correspond to those indicated from the analyzer work.

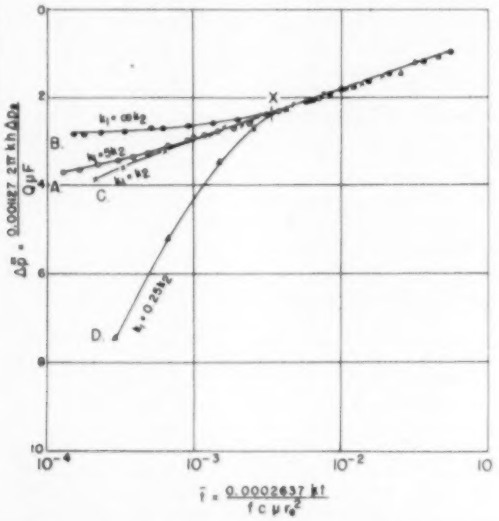

FIG. 7 — FIELD BUILD-UP CURVES; WELLS PRODUCING HIGHLY UNSATURATED FORMATIONS WITH FLOW INTO WELL BORE NEGLIGIBLE.

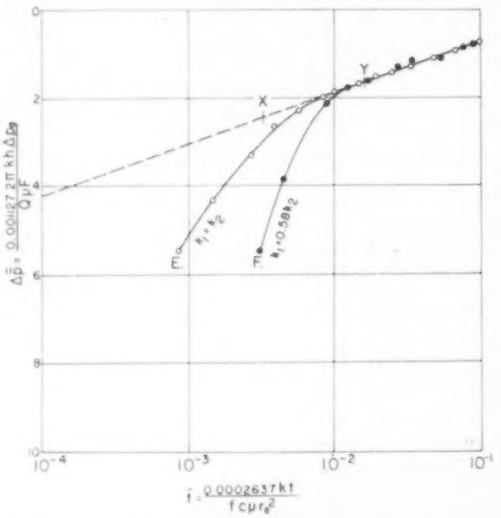

FIG. 8 — FIELD BUILD-UP CURVES; WELLS PRODUCING UNSATURATED FORMATIONS WITH FLOW INTO WELL BORE APPRECIABLE.

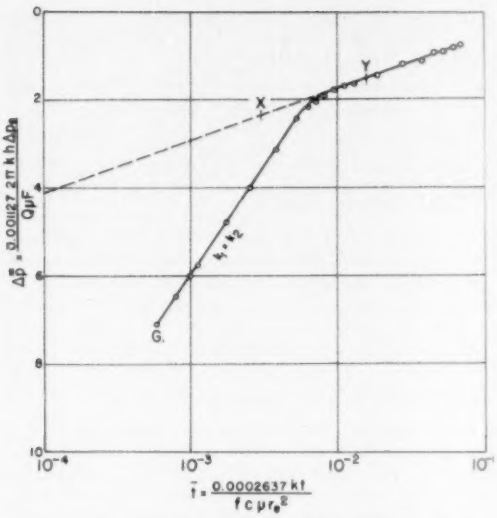

FIG. 9 — FIELD BUILD-UP CURVE; WELL PRODUCING FORMATION WITH OIL AND GAS FLOWING.

SUMMARY

The relationships developed in this paper enable the reservoir engineer to estimate the effective permeability and reservoir pressure from the early portion of the build-up curve provided the well is stabilized prior to shut-in. Relations are also presented to assist planning the pressure survey for estimating the length of time of constant production to stabilize the well and the shut-in time required to obtain sufficient data for analysis.

The method for analysis of build-up curves was derived for the flow of a homogeneous compressible liquid. However, the method may be extended to include an approximation for the condition of oil and gas flow in the reservoir where the gas is distributed throughout the reservoir rather than contained in a cap.

The early part of the build-up curve is independent of the amount of migration over the external boundary, and this portion of the curve is used for permeability estimation. It is not necessary therefore to know the magnitude of this migration for permeability estimation.

The build-up characteristics for the two cases of maximum and zero migration over the external boundary were considered. The difference in final build-up pressure for the two cases may be significant. It is therefore necessary to assume a value for the magnitude of migration in the estimation of reservoir pressure by this method. From the 80 wells studied, some of which were produced at relatively high allowables from zones of permeability in the order of one millidarcy, the error possible from the mid-value was found to be as large as 50 psi. High production rates and low permeabilities both lead to increases in the uncertainty arising from estimation of the degree of migration. This error would be practically constant in succeeding determinations, and the reservoir pressure decline would be considerably more accurate.

The equations developed for build-up characteristics consider a well producing from a uniform formation and shut in at the sand face. The existence of a high or low permeability zone in the immediate vicinity of the well and the flow into the well bore after shut-in to compress the fluids contained therein cause a deviation from the equations. Studies with the electrical analyzer show that such deviation is appreciable only in the very early portion of the build-up curve, becoming negligible after a short period of time, and these very early data should not be considered in interpreting build-up curves by this method.

The methods developed here are for a well stabilized prior to shut-in. The electrical analyzer may be used to extend this approach to instances in which the well is not stabilized prior to shut-in. However, analyzer runs take considerably longer to make than the method described here.

The permeability estimated from the build-up curve represents the permeability in the majority of the drainage area away from the well. The permeability estimated from the productivity index using Darcy's Law represents the permeability throughout the drainage area. Thus, the existence of a high or low permeability zone in the immediate vicinity of the well may be estimated by comparison of the permeabilities determined in these two ways. This offers a method to evaluate the possibility of having damaged the well in drilling or benefits occurring from treatment.

ACKNOWLEDGMENT

The authors wish to express their appreciation to Francis Collins, W. W. Schriever and V. J. Sikora for their suggestions and assistance in connection with this problem.

NOMENCLATURE

c = mean liquid compressibility, psi^{-1}
C = saturation, fraction
f = reservoir porosity, fraction
F = formation volume factor, $\frac{\text{Res bbl}}{\text{STB}}$
h = reservoir thickness, ft
k = effective permeability, millidarcys
K = diffusivity, $\frac{k}{fc\mu}$
m = slope of build-up curve = $\Delta p/\log t_e/t$
p = pressure, psia
Q = volume rate of flow, STB/Day
r = radial distance measured from center of well, ft
$\bar{r}$ = r/r_w
R = gas-oil ratio, $\frac{\text{SCF}}{\text{Bbl}}$
S = solubility, $\frac{\text{SCF}}{\text{Res Bbl}}$
t = time, hours
v = velocity
μ = viscosity, centipoise
δ = density, lb/ft^3
ρ = gas conversion factor, $\frac{\text{SCF}}{\text{bbl}}$
ψ = mass rate of flow

Functions

ln = logarithm to the base e
log = logarithm to the base 10
$U(a_n r) = Y_1(a_n r_e) J_o(a_n r) - J_1(a_n r_e) Y_o(a_n r)$
$U'(a_n r) = a_n Y_1(a_n r_e) J_1(a_n r) + a_n J_1(a_n r_e) Y_1(a_n r)$
$U'(a_n f_w) = 0$
f(λ) = time function of flux
g(r) = initial density distribution function
J = Bessel function of first kind
Y = Bessel function of second kind
$x_n = a_n r_w$

$$\Delta\bar{p} = \frac{0.001127\ 2\pi kh}{Q\mu F}\Delta p_f$$

$$\bar{t} = \frac{0.0002637\ kt}{fc\mu r_e^2}$$

$$\Delta\bar{p} = \frac{0.001127\ 2\pi kh}{Q\mu F}\Delta p_e$$

$\Delta p_f = p - p_f$
$\Delta p_e = p_e - p$

$$K' = \frac{k(\delta_L + \delta_g R)}{fc_T \mu_L (F\delta_T)}$$

Subscripts

e = conditions at radius of drainage
w = conditions at well
f = conditions with well flowing
g = gas phase
L = oil phase
o = initial conditions
r = relative
T = condition of the total system
s = static conditions
1 = in area near well
2 = in area away from well

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APPENDIX

Theoretical Build-up Relations

The fundamental differential equation defining the flow of a compressible homogeneous fluid through a porous medium in a radial flow system with no vertical flow is the familiar diffusivity equation

$$\frac{\partial^2\delta}{\partial r^2} + \frac{1}{r}\frac{\partial\delta}{\partial r} = \frac{1}{K}\frac{\partial\delta}{\partial t} \qquad (1)$$

Before the integration of this equation for application to the problem at hand certain stipulations concerning the conditions of the reservoir and its fluid must be specified as boundary conditions. Muskat[5] has applied the equation to obtain the build-up relations for the following conditions:

1. An undersaturated fluid is flowing in the reservoir.
2. There is a steady state distribution in the reservoir prior to shut-in.
3. The well is shut in at the bottom. This excludes the possibility of flow into the well bore after shut-in due to the compressibility of the fluids.
4. A constant density and thus pressure is maintained at the external boundary, radius of drainage, during the build-up period.

This final specification of constant pressure at the external boundary at steady state indicates a reservoir under the condition of maximum migration of fluid across the external boundary for the given pressure difference between the external boundary and the well. This migration of course will be equal to the production rate at the time of shut-in and will drop to zero as the pressure is built up. By a direct integration of Darcy's Law the initial steady state density distribution for these conditions may be obtained in the form

$$\delta = \frac{\delta_e - \delta_w}{\log \bar{r}_e}\log \bar{r} + \delta_w \qquad (2)$$

Applying these boundary conditions to the diffusivity equation an integration results in an equation for the build-up characteristics which expressed in dimensionless variables takes the form as presented by Muskat

$$\frac{p_e - p}{p_e - p_f} \simeq \frac{\delta_e - \delta}{\delta_e - \delta_f} = \frac{2}{\ln \bar{r}_e}\sum_{n=1}^{\infty}\frac{e^{-x_n^2\bar{t}}}{(x_n)^2 J_1^2(x_n)} \qquad (3)$$

where $J_1(x_n) = 0$. The dimensionless variable $\bar{t}$ is defined by the equation

$$\bar{t} = \frac{0.0002637\ kt}{f c \mu r_e^2} \quad \ldots\ldots\ldots (4)$$

where time is in hours, permeability in millidarcys, porosity as a fraction, compressibility in psi^{-1}, viscosity in centipoises, and radius in ft. Pressures may be substituted for density as was done in equation (3) because of the relation evolved from the equation of state where

$$\delta = \delta_o e^{c(p_o - p)} = \delta_o[1 + c(p_o - p)] \quad \ldots (5)$$

The conditions that exist at the radius of drainage may vary from a case of constant pressure at the external boundary to a condition of no influx as in a closed drainage area. It was therefore desirable to obtain equations defining the build-up characteristics for both cases as conditions of extremes at the external boundary or radius of drainage of the well.

The stipulations concerning the reservoir and its fluid that are specified in connection with obtaining the build-up characteristics for a well in a closed drainage area with no influx over the external boundary are the same as those just presented, with the exception of condition (4), which must be changed to consider the influx at the external boundary to be zero. This then represents a radial system in which the flux is specified over both boundaries. A system of this nature is governed by the equations[5] as derived from the diffusivity equation

$$\delta = \frac{2K}{r_e^2 - r_w^2}\int_0^t [f_e(\lambda) - f_w(\lambda)]\,d\lambda + \frac{2}{r_e^2 - r_w^2}\int_{r_w}^{r_e} rg(r)\,dr$$

$$+ \pi \sum_{n=1}^{\infty} \frac{a_n^2 J_1(a_n r_w)\,U(a_n r)\,e^{-Ka_n^2 t}}{J_1^2(a_n r_w) - J_1^2(a_n r_e)} \left[\frac{\pi}{2} J_1(a_n r_w) \int_{r_w}^{r_e} rg(r)\,U(a_n r)\,dr \right.$$

$$+ K \frac{J_1(a_n r_e)}{a_n r_w} \int_0^t f_w(\lambda) e^{Ka_n^2 \lambda}\,d\lambda - K \frac{J_1(a_n r_w)}{a_n r_e} \left. \int_0^t f_e(\lambda) e^{Ka_n^2 \lambda}\,d\lambda \right] \quad (6)$$

where a_n is determined by the equation

$$U'(a_n r_w) = 0 \quad \ldots\ldots\ldots (7)$$

For the special case of a shut-in well in a closed reservoir that is considered here the flow function is zero at both boundaries.

$$f_w(\lambda) = f_e(\lambda) = 0 \quad \ldots\ldots\ldots (8)$$

The initial density distribution for this case is obtained in the same manner as before. This distribution, however, represents an equilibrium condition which is reached in the drainage area when the gradient is constant with time at all points.[5] Applying Darcy's Law as before the initial density distribution may be expressed in the form

$$g(r) = \delta_w + \frac{\psi c \mu}{4\pi k h (r_e^2 - r_w^2)} [2r_e^2 \ln \bar{r} + r_w^2 - r^2] \quad \ldots (9)$$

Making use of this expression in equation (6) the general expression for density as a function of position and time is

$$\delta = \delta_w + \frac{\psi c \mu}{2\pi k h} \left[r_e^2 \frac{(r_e^2 \ln r_e - r_w^2 \ln r_w)}{(r_e^2 - r_w^2)^2} - \frac{1}{2} - \frac{r_e^2 + r_w^2}{4(r_e^2 - r_w^2)} \right.$$

$$\left. - \frac{r_e^2 \ln r_w}{r_e^2 - r_w^2} + \frac{\pi^2}{2} \sum_{n=1}^{\infty} \frac{J_1^2(a_n r_w)\,U(a_n r_w)\,U(a_n r)}{J_1^2(a_n r_e) - J_1^2(a_n r_w)} e^{-Ka_n^2 t} \right] \quad \ldots\ldots (10)$$

In this particular application of this equation the interest is in the pressure, and thus the density, at the bottom of the well, requiring that $r = r_w$ be substituted in the Bessel function $U(a_n r)$.

The resulting density equation can then be converted to an equation for the bottom hole pressure using equation (5). Furthermore, the volume rate of flow is expressed by $FQ = \psi/\delta$ and in the terms involving r_e and r_w the r_w terms may be neglected without error since $r_e >>> r_w$. The pressure build-up expressed in dimensionless variables is

$$\Delta\bar{p} = \ln \bar{r}_e - \frac{3}{4} + \frac{\pi^2}{2} \sum_{n=1}^{\infty} \frac{J_1^2(x_n) U^2(x_n)}{J_1^2(\bar{r}, x_n) - J_1^2(x_n)} e^{-\bar{r}_e^2 x_n^2 \bar{t}} \quad (11)$$

The equation determining x_n is

$$J_1(\bar{r}_e x_n) Y_1(x_n) - J_1(x_n) Y_1(\bar{r}_e x_n) = 0 \quad \ldots (12)$$

The dimensionless variable proportional to pressure, $\Delta\bar{p}$, is defined by the equation

$$\Delta\bar{p} = \frac{0.001127\ 2\pi k h}{Q\mu F} \Delta p \quad \ldots\ldots (13)$$

where permeability is in millidarcys, height in ft, production in stock tank barrels per day, viscosity in centipoises, and pressure in psi. From equations (11) and (12) the pressure at the bottom of a shut-in well in a closed reservoir may be calculated as a function of time.

Equations (3) and (11) define the build-up characteristics for the two extremes in the magnitude of influx over the external boundary. For purposes of comparison of the numerical solutions of these equations it is necessary to convert $\frac{p_e - p}{p_e - p_i}$ to $\Delta\bar{p}$ or vice versa. Conversion of the former to $\Delta\bar{p}$ is accomplished by means of the well-known radial flow equation

$$Q = \frac{0.001127\ 2\pi k h \Delta p_i}{F\mu \ln \bar{r}_e} \quad \ldots\ldots (14)$$

Using this relation the conversion equation takes the form

$$\Delta\bar{p} = \left[1 - \frac{p_e - p}{p_e - p_i} \right] \ln \bar{r}_e \quad \ldots\ldots (15)$$

and equation (3) may be expressed as

$$\Delta\bar{p} = \ln \bar{r}_e - 2 \sum_{n=1}^{\infty} \frac{e^{-x_n^2 \bar{t}}}{(x_n)^2 J_1^2(x_n)} \quad \ldots (16)$$

A plot of $\Delta\bar{p}$ vs $\log \bar{t}$ for equations (11) and (16) shows an apparent straight line section in the $\bar{t}$ range of 10^{-4} to 5×10^{-3}. This section, however, is not actually a straight line as might be determined by proper differentiation of

equation (11) or (16). For practical purposes, though, this is a straight line and will be used as such. The straight line sections calculated from equation (16) are parallel since translation by the quantity $\ln \bar{r}_e$ results in coincident curves. Only one numerical evaluation of equation (11) was made, and this curve when translated by $\ln \bar{r}_e$ will coincide with those from equation (16). Electrical analyzer curves of equation (11) for various values of $\bar{r}_e$ show this same property of coincidence when translated by $\ln \bar{r}_e$. The slope of the build-up curve in the straight line section is important in that it is proportional to the permeability according to the relation

$$\frac{\Delta(\Delta\bar{p})}{\Delta(\log \bar{t})} = \frac{kh}{141.2\ Q\mu F} \frac{\Delta(\Delta p)}{\Delta(\log t)} \quad . \quad . \quad . \quad . \quad (17)$$

Substituting the slope of the calculated curve (1.147) for $\frac{\Delta(\Delta\bar{p})}{\Delta(\log \bar{t})}$ in this equation results in an equation for the effective permeability as a function of the slope, m, of the straight line section of the build-up curve. This equation is

$$k = \frac{162.5\ Q\mu F}{hm} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Build-up Curves — Two-Phase Flow

The relationships that have been developed to this point have considered the flow of a homogeneous compressible liquid through a porous medium. It would be, of course, advantageous to extend this method to include drainage areas in which both oil and gas were flowing. By making the approximations that are noted, this was done in the following manner.

By a material balance of the residual oil the mass transfer is expressed by the equation as modified from the approach of Muskat and Meres[10]

$$\nabla \cdot \frac{\delta_L k k_{rL}}{\mu_L F} \nabla p = -f \frac{\partial}{\partial t}\left(\frac{\delta_L C_L}{F}\right) \quad . \quad . \quad (19)$$

The general equation for gas flow is

$$\nabla \cdot \frac{\delta_g k k_{rL}}{\mu_L F} S \nabla p + \nabla \frac{\delta_g k k_{rg}}{\mu_g} \rho \nabla p = -f \frac{\partial}{\partial t}\left(\delta_g C_g \rho + \frac{\delta_g C_L}{F} S\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

In the reservoir away from the well the pressure is fairly constant, and the pressure functions, μ_L, μ_g, F, ρ, and S are assumed to be considered constant. Likewise, the saturation is fairly constant and the dependent variables k_{rg} and k_{rL} will be assumed constant also. Applying these assumptions to the above equations the expression for gas flow becomes

$$k\left(\frac{k_{rL}\delta_g S}{\mu_L F} + \frac{k_{rg}\delta_g \rho}{\mu_g}\right) \nabla^2 p = -f \frac{\partial}{\partial t}\left(\delta_g C_g \rho + \frac{\delta_g C_L}{F} S\right) \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Applying the same to liquid flow

$$k\left(\frac{\delta L^s_{rL}}{\mu_L F}\right) \nabla^2 p = -f \frac{\partial}{\partial t}\left(\frac{\delta_L C_L}{F}\right) \quad . \quad (22)$$

Adding these last two equations a general equation for the simultaneous flow of oil and gas through a porous medium is obtained. This is

$$k \frac{k_{rL}}{\mu_L F}\left(\delta_L + \delta_g S + \frac{\delta_g k_{rg} \mu_L F \rho}{k_{rL}\mu_g}\right) \nabla^2 p = -f \frac{\partial}{\partial t}\left(\frac{\delta_L C_L}{F} + \delta_g C_g \rho + \frac{\delta_g C_L}{F} S\right) \quad . \quad . \quad (23)$$

The right side of this equation is a function of the total density, δ_T, of the system and may be converted to pressure by the introduction of a total compressibility term, c_T (see equation 5). Upon collection of constants the equation takes the form

$$\nabla^2 p = \frac{1}{K'} \frac{\partial p}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

where

$$K' = \frac{k \frac{k_{rL}}{\mu_L F}\left[\delta_L + \delta_g R\right]}{f c_T \delta_T} \quad . \quad . \quad . \quad . \quad (25)$$

since

$$R = \frac{k_{rL}\mu_L F \rho}{k_{rL}\mu_g} + S \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

Equation (24) is of the same form as the diffusivity equation for single-phase flow, and its solutions for the rise in bottom hole pressure when the well is shut in may be obtained by analogy.

The initial steady state presure distributions to be considered may be derived with the same conditions applying as were considered for single-phase flow with slight modifications

$$\int_{p_w}^{p} \frac{kh}{\mu F}\, dp = \frac{893\ Q}{2\pi} \ln \frac{r}{r_w} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

for constant pressure maintained at the external boundary and

$$\int_{p_w}^{p} \frac{kh}{\mu F}\, dp = \frac{893\ Q_L}{2\pi}\left(\ln \frac{r}{r_w} - \frac{r^2}{2r_e^2}\right) \quad . \quad (28)$$

for a closed drainage area. Since it appears that during much of the history of the field when two phases are flowing, the saturation throughout the entire reservoir is relatively constant at any time the permeability may be considered constant. Although the pressure varies considerably, particularly near the well, the μF product will nevertheless remain fairly constant since μ increases and F decreases with pressure decline. With these assumptions the initial density distributions may be shown to take the same form as before, equations (11) and (16).

From these considerations the dimensionless variable proportional to pressure, $\Delta\bar{p}$, is defined as before,

$$\Delta\bar{p} = \frac{0.001127\ 2\pi kh}{Q_L \mu_L F_L} \Delta p \quad . \quad . \quad . \quad . \quad (29)$$

The dimensionless variable proportional to time, $\bar{t}$, now requires a substitution of K′ for the diffusivity, K, in equation (4) giving

$$\bar{t} = \frac{0.0002637\ k}{f c_T \mu_L r_e^2}\left(\frac{\delta_L + \delta_g R}{F \delta_T}\right) t \quad . \quad . \quad . \quad (30)$$

This change, however, does not require any changes in the equation for effective oil permeability which is

$$k = \frac{162.5\ Q_L \mu_L F_L}{hm} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

The pressure variables in these equations should be evaluated at or near the average reservoir presure, and with these modifications a well producing two phases may be handled in the same manner as a well producing only oil. ★ ★ ★

T.P. 2852

SOME THEORETICAL CONSIDERATIONS RELATED TO THE QUANTITATIVE EVALUATION OF THE PHYSICAL CHARACTERISTICS OF RESERVOIR ROCK FROM ELECTRICAL LOG DATA

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INTRODUCTION

The use of electrical well logs for the quantitative determination of such reservoir parameters as connate water saturation, formation permeability and connate water salinity has recently been attracting the attention of a number of workers[1,2,3,4,5].

While the theory of the determination of connate water salinity from the self potential S.P. log has received rather detailed treatment, relatively little attention has been paid to the theoretical aspects involved in the quantitative interpretation of resistivity data. It is clear that if electrical well logs can be used for the quantitative evaluation of physical characteristics of reservoir rock, they will provide a valuable tool to supplement cheaply information obtained by more laborious core analysis. In certain cases it is conceivable that the coring program could be considerably curtailed if the electric log could be relied upon to give reasonably accurate quantitative information.

It is our object in this paper to examine the theoretical basis of quantitative log interpretation as expressed in such well-established logging concepts as formation factor and cementation factor. It is also our object to investigate the physical aspects of the relationship which is presumed to exist between resistivity index and brine saturation in reservoir rock. In particular, we will endeavor to draw attention to the fact that it is possible to express these logging concepts in terms of capillary pressure-saturation relationships, permeability and tortuosity, parameters which we will consider in this paper to be fundamentally indicative of rock texture. The probability of being able to obtain from log recordings alone the data theoretically essential to permit quantitative log interpretation will be examined, and consideration will also be given to the problem of formulating simple semi-empirical relationships for use in the field.

THEORETICAL CONSIDERATIONS

The concept of formation resistivity factor, or as it is now commonly called, formation factor, appears to have been introduced by G. E. Archie[6,14]. Formation resistivity factor as defined by Archie is the resistivity of a rock 100 per cent brine-saturated divided by the resistivity of the brine. This relationship had previously been used by physical chemists and the concept is, for example, implicit in an early treatment by Fricke[7] of the conductivity of aqueous slurries. Archie was able to establish the fact that although the relationship between formation factor and porosity did not change too greatly for different rock textures, the relationship between formation factor and permeability was markedly dependent on rock texture. The relationship found by Archie between formation factor and porosity was expanded by H. Guyod[8]. Archie had suggested that the formation factor, F, could be expressed in terms of the porosity, ϕ, as follows:

$$F = \phi^{-m} \quad . \quad . \quad . \quad . \quad (1)$$

where, ϕ = effective porosity fraction of the sand,

and, m = an exponent greater than about 1.3.

Guyod introduced the term cementation factor for the exponent, m, since it may be qualitatively shown that formation factor for any given porosity tends to increase as the sand becomes more cemented. It would appear that the concept of m as an exponent representing the cementation in a sand is strictly only of qualitative value, since the quantitative estimation of m by means other than the determination of F and ϕ has not been possible. Guyod suggests that m can be estimated from a visual examination of a sample of rock, but this method appears to be both arbitrary and unreliable. It can be said, however, that in intergranular reservoirs of practical interest, the range of m is from about 1.4 to 3.0. A possible explanation for the fact that m is found to lie between these limits will be offered below.

The determination of formation factor is an essential preliminary to the

[1] References given at end of paper.

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employment of the electric log for either the qualitative or quantitative interpretation of reservoir rocks for oil saturation. By Archie's original definition, F is a ratio and is independent of the resistivity of the brine used to saturate the formation. As shown elsewhere[9] this definition of F has implicit in it the assumption that the solid matrix of the formation is an insulator. If the solid matrix is a conductor, F will not be independent of the resistivity of the saturating fluid. However, in ideal cases a correction may be made for the presence of conductive solids in the rock matrix and if this correction is made, it is theoretically possible to determine F from log data.[9]

The calculation of the resistivity of the connate water in the formation may be made if the electrochemical S.P. applicable to the formation and the mud activity are both known.[5] The resistivity that the formation would have, if it were 100 per cent saturated with connate water, is then the product of the formation factor and connate water resistivity. A qualitative indication of the presence of oil or gas in the formation may be obtained by comparing this resistivity with the true resistivity of the formation obtained from resistivity departure curves.[16]

It may be said that, qualitatively, the effect of oil or gas in the formation will be to increase the resistivity of the formation. It has been widely assumed that the amount of oil or gas in the formation (if the formation has integranular porosity) may be calculated quantitatively from the relationship.

$$\text{Resistivity Index} = S_w^{-n} = I \quad . \quad (2)$$

where I, the resistivity index, is the ratio of the resistivity of the formation in situ to the resistivity which it would have at the same temperature if 100 per cent saturated with connate water, and S_w is the fraction of the pore volume saturated with connate water. The exponent, n, is normally given the value of 2.

This relationship, which is fundamental to the quantitative interpretation of electrical well logs, does not appear to us to have the requisite theoretical and experimental justification to warrant the universal applicability which is generally attributed to it. The relationship, in fact, appears to rest on the experimental findings of Wyckoff and Botset,[11] as supported by the work of Jakosky and Hopper,[12] Martin, Murray and Gillingham,[13] Leverett[20] and others. Some confirmation was also provided by Morse, Terwilliger and Yuster.[15] The data obtained by all these workers apply in most cases to unconsolidated sands, although a few data are applicable to moderately cemented sandstones. It is, however, important to note that the saturation processes used by these workers may not have always resulted in the same type of fluid distributions as that obtaining in reservoir rocks. The exponent found by these workers is actually an average of 1.96, although 2 is customarily assumed for log interpretation. The probability of this exponent being a universal constant for all reservoir rocks, irrespective of their texture, will be considered below, together with a consideration of the dependency of this exponent on fluid saturation distribution.

It will suffice to say here that available experimental evidence is not always correlatable to Equation 2, if the exponent n is assumed to be constant. It may be pointed out that the data of Morse, Terwilliger and Yuster, if substituted in Equation 2, will show an exponent which is not constant but varies from 8.5 at 90 per cent saturation to 2.8 at lower saturations. These results are for certain Bradford cores when using oil displacement of the brine and the variable exponents were attributed by these workers to the oil wettability of the sand. Henderson and Yuster[16] and Henderson and Mendrum[17] show a similar variation of the exponent n in a given sand depending upon the kind of non-wetting phase, the applied pressure inducing two-phase flow and other factors which affect the configuration of the non-wetting phase. Similarly, Guyod[18] has published a number of data showing the relationship found by Russian workers between resistivity index and saturation for cores of varying porosity when different types of non-wetting phase were employed. These data show that the water saturation index exponent is not independent of saturation and in addition varies from 1.7 to 4.3 at high water saturations, depending upon the type of porous medium and the nature of the non-wetting phase. The results, however, tend in most cases to an exponent of about 2.5 at water saturations less than 20 per cent. No details are available regarding the experimental technique employed by the Russian workers. Variable values of the exponent apparently less than 2 are explicable if formations contain conducting solids[9] but values of the exponent as high as 4.3 imply either a gross experimental error or a marked influence of formation texture or type of distribution of the conducting phase on the results obtained.

The effect of the formation texture on the validity of the resistivity index-saturation relationship does not appear to have been considered in detail either experimentally or theoretically. However, in recent years much information concerning methods of describing rock texture in terms of such parameters as tortuosity and specific internal surface area have been formulated by Carman[19] and others. These concepts recently have been linked to the study of capillary pressure phenomena in porous media.[29] It would appear that these rock textural relationships may be used also to give a more fundamental definition to formation factor and from this definition a theoretical treatment may be given to the concept of cementation factor and the exponent in the resistivity index-saturation relationship.

In order to accomplish this end, which involves the interrelation of electrical parameters with those relating to fluid movement, we make the fundamental assumption that the tortuosity pertaining to the flow of electrical current through conducting fluids in porous media is closely related to the tortuosity which appears in equations describing the mass transfer of fluids in the same media.

Tortuosity, it will be recalled, refers to the effective flow streamline length which determines the macroscopically observed variation in conductivity (whether it be electrical or fluid) as a function of the miscroscopic orientation characteristics of the individual pores comprising the interspaces. Therefore, the equivalence of hydraulic and electrical tortuosities seems to de-

pend to some extent on the degree of uniformity of the pore structure.

In the treatment given below we will, for simplicity, assume that these two tortuosities are numerically identical and we will show that there is evidence in a number of cases to support this view. We would not, however, deny the contention that there may be an empirical constant connecting the two tortuosities; such evidence as we have obtained points, however, to such a constant, if it exists, being close to unity.

We would not infer that the mechanism of flow of electrical current through a porous medium containing a conducting fluid is identical with the flow mechanism of the fluid itself through that medium. Differences between the two mechanisms are immediately apparent and certain of these differences are discussed below. In particular we would not expect any similarity between the two processes unless the path available for hydraulic movement was the same as that available for electrolytic conduction. This limitation excludes any consideration of such porous media as shales, where the solid matrix is itself conducting. Similarly, in a porous medium composed of both conducting and non-conducting solids the similarity between fluid flow and electrolytic conduction can only be presumed to exist throughout the liquid phase. That is, any conductivity resulting from the presence of the conducting solids in the matrix must first be accounted for by independent processes.

Development of Formation Factor Concepts

The foregoing considerations imply that the formation factor concept is of fundamental importance to the development of applications based on electrical log data. From this, it follows that a definition of formation factor in terms of textural parameters of greater significance than the arbitrary cementation factor, m, of Equation 1 would be of considerable importance in the wider interpretation of electrical log data. Such a definition may be derived if the tortuosity applicable to fluid flow in porous media is assumed to be the same as that which affects the resistivity of porous media to electrolytic conduction.

In considering the electrical resistance of a fluid saturated porous medium possessing a random* distribution of pores, we may express the resistance in terms of the electrical resistance of a single fluid-filled channel having a rather complex shape but of constant cross sectional area, ϕA_c, where ϕ is the fractional porosity and A_c is the total area of cross section. The length of this conducting channel may be taken as L_a, where L_a is greater than the actual length, L, of the porous medium. If ρ_c is the resistivity of the saturating fluid and ρ_w the resistivity of the saturated medium,

$$\rho_w \cdot \frac{L}{A_c} = \rho_c \cdot \frac{L_a}{\phi A_c}$$

Whence, $$\rho_w = \rho_c \frac{L_a/L}{\phi}$$

But, by definition,

$$F = \rho_w/\rho_c = (L_a/L)/\phi = T^{1/2}/\phi \quad . \quad . \quad . \quad . \quad (3)$$

Where, $T = (L_a/L)^2$ = Tortuosity. It may be pointed out that Thornton's[21] recent treatment of relative permeability data has implicit in it concepts which lead also to Equation 3. In an extension of Thornton's treatment we derived[20] an expression for the hydraulic formation factor, F_f, in the form:

$$F_f = NT/\phi^2 \quad . \quad . \quad . \quad (4)$$

Where N = number of pores in any cross-sectional area, A_c.

Comparison of Equations 3 and 4 gives:

$$F_f/N = F^2$$

and this calls attention to a fundamental difference between viscous resistivity to fluid flow and electrical resistivity. The former effect depends principally on the pore radius raised to the fourth power (r^4) and the latter to the radius squared (r^2). Hence, we observed that F_f from Equation 4 is the square of F from Equation 3 but includes an arbitrary parameter reflecting porous body geometry.

It is necessary now to examine Equation 3 in detail, especially with regard to its implications, since this definition of formation factor will serve as the basis for much of the other development to be given in this paper.

* Note that the fundamental definition of a porous medium possessing random pore distribution is that any plane through the medium will always expose a constant fractional void area proportional to the porosity.

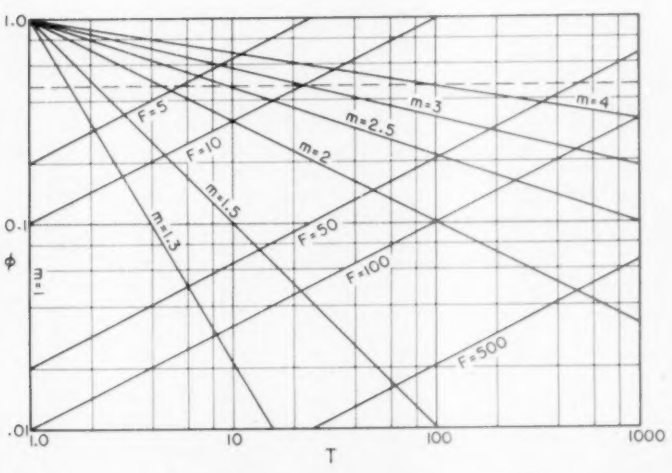

FIG. 1 — POROSITY AS A FUNCTION OF TORTUOSITY FOR CONSTANT VALUES OF FORMATION FACTOR AND CEMENTATION FACTOR

Fig. 1 is a plot of fractional porosity versus tortuosity where a graphical solution can be made of Equation 3 for the formation factor. The dashed horizontal line refers to the porosity of the cubic packing of spheres, which is the maximum theoretical regular packing porosity which can obtain and which is somewhat above the maximum porosity which will obtain in practical instances. Minimum porosities for granular materials will generally exceed 0.05, and tortuosities will range from about 2.5 to perhaps 250; meaning the formation factors will generally fall in the range of 2.5 to perhaps 500. Fig. 1 also shows isocementation factor lines which are based on the following formulation for the cementation factor, m:

$$m = (\ln\phi/\ln T^{1/2})/(\ln\phi) \quad . . \quad (5)$$

arrived at by combining Equations 1 and 3. Although m can vary in the mathematical sense between 1 and infinity, it is clear from Fig. 1 that the variation to be encountered in practice lies well within the limits of 1.3 and 3.0 as originally observed by Archie, Guyod and others.† In the theoretical sense, however, values of m and limits in values of m are of little consequence since Equation 3 appears to be the fundamental definition of formation factor and Equation 1 is nothing more than a trivial definition which has been accepted in the past because of the coincidental fact that m appears to have a rather constant value in certain reservoirs. The theoretical implication of finding a reservoir where m is a true constant is that tortuosity will be equal to porosity raised to some constant exponent, $(2-2m)$. Previous investigations,[20] however, have shown that tortuosity may be expressed:

$$T = (\phi/Kt_s)(\delta/P_d)^2 \quad \text{(contact angle assumed 0)} \quad . . . . . \quad (6)$$

where δ and P_d are the interfacial tension and the displacement pressure, respectively, and t_s is the pore shape factor referred to by Carman.[20] This would give as another definition for m:

$$m = (1/2\ln\phi + 1/2\ln K + 1/2\ln t_s + 1/2\ln P_d/\delta)/(\ln\phi)$$

implying that a log log plot of ϕ versus $(\delta/P_d)/(Kt_s)^{1/2}$ would be linear with slope equal to $(1-2m)/2$ and with zero intercept if m were constant. However, for texturally similar porous media, i.e., with identical tortuosities, it is seen from Equation 6 that this plot will have a slope of (-2) and intercept equal to T, and that for texturally dissimilar porous media the slope of $(1-2m)/2$ and zero intercept is not at all theoretically indicated as a unique requirement.

Equation 6 is of further interest in developing the relationship between formation factor and permeability. Combination with Equation 4 gives:

$$\ln F = -1/2 \ln K + \ln(\delta/\phi^{1/2}t_s^{1/2}P_d)$$

which is a reasonable description of some of Archie's data[14] where a log log plot of F and K gave a slope of $-1/2$. The implication is that the term, $\delta/\phi^{1/2}t_s^{1/2}P_d$, was constant for the reservoirs giving such data plots. Such constancy, however, is not to be anticipated as unique since the above referred to intercept term can also be expressed as $(TK)^{1/2}/\phi$, showing its implicit dependence on K; and indeed Archie's data more generally show a slope of about $-1/4$ on the log log plot of F versus K.

To conclude this discussion of formation factor as described by Equation 3, it is of interest to examine further the utility of the expression which has been developed. For instance, the claim that Equation 3 is a more theoretically sound description of F than is Equation 1 will have little or no appeal to those concerned with practical applications unless it can be shown that the term T in Equation 3 is more readily obtainable than the cementation factor,

Table I

Tortuosity of Regular Sphere Packings

Packing	F (Pirson)	ϕ	T	$T=(3-\phi/2)^2$
Cubic	2.64	.476	1.57	1.60
Rhombic	3.38 - 4.40	.395	1.33 - 1.73	1.70
Hexagonal	5.81	.259	2.26	1.88

Table II

Core	K md	ϕ	P_d psi	δ dynes/cm	F Measured	F Computed
Alundum	693	0.258	0.75	43.0	13.7	15.6
Alundum	667	0.254	1.05	43.0	11.3	11.0
Alundum	688	0.265	0.994	43.0	11.9	11.2
Alundum	657	0.262	1.05	43.0	13.0	11.0
Pyrex	2300	0.344	0.653	43.0	7.2	8.1
Nicholls Buff	232	0.200	1.73	43.0	12.5	12.8
Nicholls Buff	205	0.198	2.10	43.0	12.4	12.3
Berea	907	0.225	0.874	43.0	11.7	12.0
Berea	695	0.226	0.880	43.0	12.7	14.5
Alundum	64	0.236	4.24	54.2	11.5	10.1
Alundum	1305	0.294	1.23	54.2	8.0	6.9
Pyrex	322	0.298	2.13	54.2	7.7	8.0
Pyrex	353	0.303	2.82	54.2	5.7	5.8
Pyrex	342	0.304	2.13	54.2	7.1	7.5
Pyrex	149	0.268	2.55	54.2	8.4	10.3
Pyrex	129	0.366	3.86	54.2	4.04	6.25
Pyrex	105	0.325	5.21	54.2	6.4	5.5
Pyrex	8.2	0.374	18.0	54.2	4.4	4.2
Pyrex	3900	0.286	0.820	54.2	6.2	5.6
Alundum	60.8	0.232	4.71	54.2	10.9	9.5

† For example, varying the porosity ten-fold from 5 to 50 per cent and varying the tortuosity 100-fold from a value of 10 to 1000 changes the cementation factor, m, by about four-fold (i.e., from 1.36 to 6.01) if maximum porosity is associated with maximum tortuosity. On the other hand, the cementation factor will vary less than one-fold (i.e., from 2.15 to 2.67) if the more reasonable assumption is made that maximum porosity should be associated with minimum tortuosity. For these hypothetical systems the formation factor, F, will vary some 100-fold from 6.3 to about 630. (cf. Fig. 1 for other comparisons of this sort).

m, appearing in Equation 1 or that Equation 3 may be used to extend the value of formation factor measurements. Even though it has been shown by reference to Equations 3 and 4 that fluid flow and electrical conduction are not strictly analogous, we nonetheless believe our assumption that the tortuous path which provides added resistance to fluid conduction is the same as that which affects electrical conductivity in porous media is both useful and accurate. More direct proof of the essential similarity between the two tortuosities, fluid and electrical, are now given. Thus, using values of formation factor in Equation 3 quoted by Pirson[23] as applicable to systems of regular packed spheres, we can arrive at the values of tortuosity shown in Table I, since porosities are known for these packings. A number of values have been quoted as the proper tortuosity values to associate with systems of regular packed spheres, as 2.47 by Hitchcock,[24] 1.69 by Dalla Valle,[25] and 2 by Carman.[10] Moreover, implicit in the work of Fricke[1] is the definition of tortuosity as $(3-\phi/2)^2$. It is seen that the computed values in Table I at least fall within the range of possible values quoted by previous workers.

Further evidence bearing on the validity of the concepts implicit in the derivation of Equation 3 has been obtained as a consequence of the experiments summarized in Table II. It has been shown above in logarithmic form that combination of Equations 3 and 6 gives an expression for formation factor as:

$$F = \frac{\delta}{P_d}\left(\frac{1}{Kt_s\phi}\right)^{1/2} \quad . \quad . \quad . \quad (7)$$

In order to check this formulation values of P_d, δ, ϕ and K were measured by conventional means on a series of core samples consisting of both synthetic and natural oil field cores. A value of $t_s = 2.25$ was assumed, and the computed values of F are given in Table II. The formation factors were then measured and corrected where necessary for the effects of conductive solids. Fig. 2 illustrates the comparison obtained between the measured and computed values of F, and the calculated correlation coefficient of 0.986 is quite indicative of the general validity of the concepts relating formation factor to tortuosity and porosity.

The conclusion which we reach from the considerations and data given is that the similarity between the two tortuosities, hydraulic and electric, in porous media is extraordinarily close and that to a first approximation at least they may be considered to be identical. The consequence is that formation factor may be expressed in terms of a tortuosity-porosity function, thus providing the link which enables the formation factor concept to be interrelated with the important equations related to fluid movement in porous media. It is thus possible to formulate an expression (Equation 7) for formation factor in terms of porosity, permeability, interfacial tension, shape factor‡ and displacement pressure, and this expression we will show below to have certain application possibilities for the determination of permeability from electrical log data.

The expression for formation factor in terms of a tortuosity-porosity function is not of direct practical utility since tortuosity is not sufficiently readily obtainable to permit porosity to be deduced rapidly from formation factor data. Further reference to this point is made in a later section.

The new formulation of formation factor serves, however, to show that the cementation factor concept has little theoretical rationale and the use of specific values of the exponent m as characteristic of certain definite degrees of cementation is to be deprecated unless used with great caution.

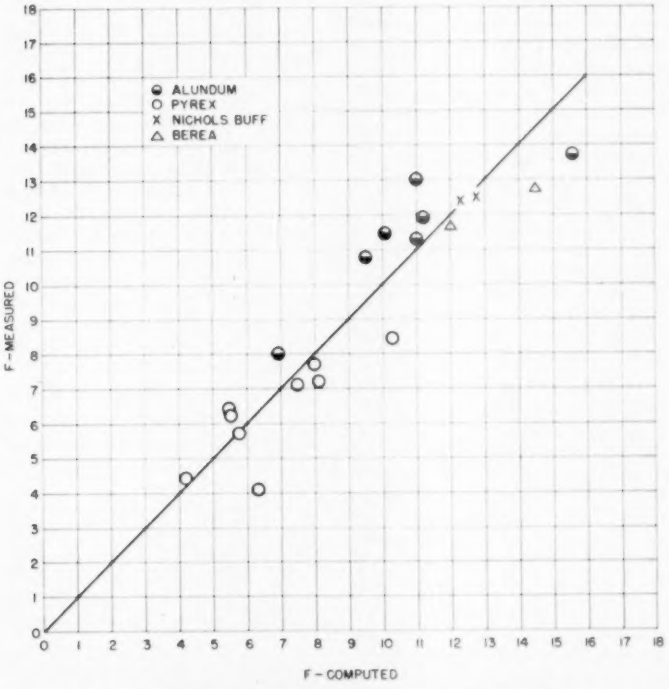

FIG. 2 – MEASURED AND COMPUTED VALUES OF FORMATION FACTOR

‡ The pore shape factor, t_s, appearing in Equation 7 has been shown by Carman[10] to vary within the narrow limits of 2.0 to 2.5, so that it may be assumed constant for computation purposes involving Equation 7.

In the case of unconsolidated porous media of relatively high porosity, the apparent constancy of m at a value of about 1.3 is probably a coincidental consequence of the compensating small changes in tortuosity which occur when the porosity of such systems is subjected to small changes.

The expression for formation factor in terms of an hydraulic tortuosity is also of considerable utility in the examination of the resistivity index concept, and we now consider this problem.

Development of Resistivity Index Concepts

By analogy to Equation 4 the effective formation factor characterizing the partially saturated porous system; that is, the ratio of the resistivity of the reservoir (or core sample) at brine saturation, S_w, to the brine resistivity, can be expressed as:

$$F_e = T_e^{1/2}/\phi S_w \quad . \quad . \quad . \quad (8)$$

where T_e is the tortuosity of the equivalent pores which may be regarded as making up the brine-filled portion of the system. Combination of Equations 3 and 8 gives:

$$I = \text{Resistivity Index} = F_e/F = (T_e/T)^{1/2}/S_w \quad . \quad . \quad . \quad (9)$$

as compared to the empirical relation which is given as Equation 2 above. The term, T_e/T, has been expressed previously[26] as:

$$T_e/T = S_w P d^2/K_{rw} P_c^2 \quad . \quad (9A)$$

where K_{rw} is the wetting liquid relative permeability and P_c is the capillary pressure, both obtaining at saturation S_w. As before we assume that the hydraulic and electrical values of T_e are the same. This gives:

$$I = P_d/P_c(K_{rw}S_w)^{1/2} \quad . \quad . \quad (10)$$

Unfortunately, there are only meager data available in the literature§ which can be employed to check the validity of equations 9 and 10, this being due principally to the fact that relative permeabilities are very difficult to measure, and when they are measured the necessary resistivity and capillary pressure data are not usually also obtained.

The first example to be considered is that of the single capillary tube saturated with various proportions of wetting (electrically conducting) and non-wetting fluids, where either the non-wetting fluid will be considered as dispersed in the wetting phase as droplets of radius less than the capillary tube radius, or the wetting liquid will be regarded as flowing as an annular cylinder around the centrally located flowing non-wetting fluid. In a recent paper[27] it was shown the right-hand term of Equation 10 reduces to $1/S_w$ for such a system, which is exactly what would be calculated for the resistivity index by Equation 9 under the conditions of saturation stated above (i.e., $T_e \simeq T$ for all values of saturation). Only one other example will be cited as direct confirmation of Equation 10. If the capillary pressure data of Leverett[28] and the relative permeability data of Wyckoff and Botset,[11] obtained on comparable unconsolidated sands, are substituted in Equation 10, the resistivity index exponent, n, is computed for all values of saturation to lie between the limits of 1.75 and 1.90 as compared with the experimentally determined value of 1.96. On the other hand, indirect evidence bearing on the validity of Equation 10 may be derived from the relative permeability data of Morse et al.,[16] even though no capillary pressure data are available for the computation. In one case values of the ratio, P_d/P_c, can be computed as 0.89 at $S_w = 0.7$, 0.84 at $S_w = 0.5$, and 0.55 at $S_w = 0.3$ (cf. Morse et al data on their synthetic core); whereas, in another case values of the ratio are computed as being greater than unity (cf. the data on the oil-wetted Bradford core). The former values are certainly reasonable and perhaps of the right order; the latter values are certainly unreasonable and perhaps explicable in terms of experimental error or in terms of an inherent limitation in the application of the equations developed in this paper to oil-wetted media. In any event, Morse et al regarded their data on the Bradford core as anomalous, at least as compared to their other results.

It will be noted that the above examples, which tend to establish the validity of Equation 10, are of interest and importance since they are suggestive that Equation 10 will be found useful as an expression for wetting liquid relative permeability. Thus, it is seen that an experiment which includes the measurement of capillary pressure and resistivity index, both as a function of saturation, suffices for the computation of K_{rw} according to:

$$K_{rw} = (P_d/P_c)^2/PS_w \quad . \quad (11)$$

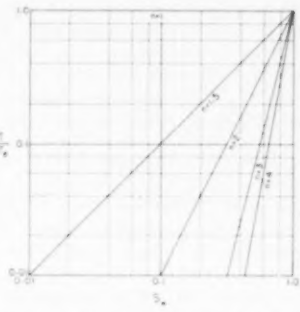

FIG. 3 — TORTUOSITY RATIO AS A FUNCTION OF SATURATION FOR CONSTANT VALUES OF THE RESISTIVITY INDEX EXPONENT

Although Equation 11 depends on assuming a variation of T/T_e with saturation to be that described by Equation 9, it should not be interpreted that previously developed expressions for wetting liquid relative permeability[32] based on assuming a constant value for T/T_e will be too greatly in error. It appears probable, in some instances at least, that T/T_e will be nearly constant as an approximation over a considerable saturation range, as evidenced by the tendency of the resistivity index exponent, n, to approach low values as the saturation is decreased (cf. the Russian data cited by Guyod[15]).**

At this point it will be instructive to examine the implications of Equation 2 as brought forth on combination of

§ Attention is called to Thornton's recent work[33] where equivalent forms of Equations 8, 9, 10 and 11 are independently developed, and where some evidence is given bearing on the validity of those equations.

** Subsequent to the preparation of this paper and subsequent to the later appearance of Thornton's note in the literature,[33] we reinvestigated the utility of Equation 11 and we reported[29] certain inherent limitations related to its application, such as the difficulty of obtaining correct values for the ratio, P_d/P_c, associated with conditions of fluid distribution characterizing multi-phase fluid flow processes. In our note we arrived at an alternative equation for relative permeability as: $K_{rw} = I^{-2}$ . . . . (11A) which is developed through interrelation of the consequences of Equation 4 with Equation 11. We also commented on the possibility of encountering experimental data which are fitted by neither Equations 11 nor 11A.

Equation 2 with Equations 9 and 10. Thus, we have:

$$n = (\ln S_w^2 T/T_o)/(\ln S_w^2) \quad . \quad (12)$$

as shown graphically by Fig. 3. As in the case of the cementation factor, m, (cf. Equation 5), we find the theoretical limits of the resistivity index exponent, n, to be between unity (as in a system of capillary tubes where T/T_o is unity for all values of saturation) and infinity. On the other hand, Fig. 3 is suggestive that the limits to be encountered in practice are perhaps 1.5 to 2.5 at saturations below 30 per cent, since from Equation 9 values of T/T_o less than about 0.01 are not to be expected. At high saturations, exponents as high as 4 appear to be possible. In connection with these practical limits, an interesting analysis can be made on the basis of Equation 12. By taking the relationships between the parameters, relative permeability, capillary pressure and saturation, as developed previously,[23] it is possible to solve Equation 12 for the exponent n. Fig. 4 shows the results of such approximation, and it is seen how n is indicated to vary with rock texture*** (as measured in terms of S_{w_i}) and with saturation. With regard to the lat-

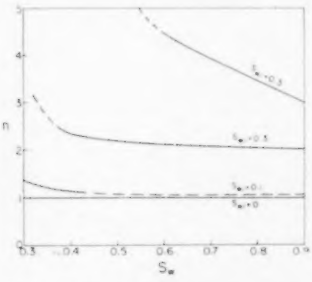

FIG. 4 — VARIATION OF RESISTIVITY INDEX EXPONENT WITH SATURATION

ter, it is our expectation that in practical instances n will be found to vary with saturation, although we do not imply that the variation as shown in Fig. 4 and arrived at by approximation processes is necessarily the type of variation which will be encountered. In fact, the majority of data available in the literature showing a variation in n with S_w in general indicate that n approaches a limiting constant value of about 2.5 or less with decreasing saturation (cf. Fig. 50 in the paper by Guyod[18]) and this is not the effect indicated by Fig. 4. Theoretically, however, at pendular saturation $I \rightarrow \infty$ and hence n must tend to infinity if S_w^{-n} is to equal I. In any event, Fig. 4 is of interest, in showing that the values of n encountered in practice are order of magnitude similar to those indicated from theory.

It is implicit in this discussion that the resistivity index exponent, n, as defined by Equations 2 and 12 is based less on theory than on the expedient desire to provide a simple empirical formulation of experimentally observed relations and in this connection our comments given previously with respect to the validity of constant values of m apply equally to values of n. It may be pointed out that if a continuous function is desired, it seems possible that the resistivity index, I, should be related by the exponent, n, to the term $(S_w - S_{w_i})$, rather than to saturation alone as in Equation 2, where S_{w_i} is the "irreducible" saturation reflecting on pendular configuration of the wetting phase. That is, our assumption regarding the equality of the hydraulic and electrical tortuosities breaks down at saturations in the vicinity of S_{w_i} because the electrical resistivity becomes a surface effect in the event the brine wets the porous matrix, or it approaches infinity at pendular saturation when the angle of interfacial contact is greater than zero and the matrix is a con-conductor. At pendular saturation all fluid conduction has, however, ceased. In this connection it will be noted that available data relating I to S_w are often consistent with the surface conductivity concept given above. For example, Morse et al[18] show a relative electrical conductivity of about 10 per cent ($n = 1.96$) at saturations which are evidently pendular for their synthetic sandstone, and equivalent results can be found in most other published data. In addition, it will be clear from Equation 12 that the exponent, n, is dependent principally on the type of saturation distribution obtaining at given values of S_w, for the ratio, T/T_o, is a measure of fluid distribution. Therefore, the requirement is implicit that in laboratory experiments fluid distributions must be obtained which are analogous to those obtaining in the natural petroleum reservoir, if data for valid electrical log interpretation are desired. Moreover, Equation 12 is quite suggestive that values of n will vary for different types of porous media, and will vary for given types of porous media when saturation is varied, even though the same type of fluid distribution is maintained, and certainly when the fluid distribution type itself is varied. Admittedly, there is only meager evidence in the published literature substantiating these possibilities, and the common occurrence of values of $n \approx 2$ is difficult to interpret except as a fortuitous and otherwise non-unique result.

DEVELOPMENT OF PRACTICAL APPLICATIONS

In addition to application for the location of shale and sand intervals, it has been suggested that electric logs yield data which may be used to determine quantitatively three important reservoir parameters, viz., connate water saturation, porosity and permeability. In the light of the foregoing theoretical discussion, it is instructive to examine the inherent probability of being able to compute these three parameters. In so doing, we must bear in mind the fact that since electric logging is now an almost universal adjunct to standard drilling practice, any quantitative or even semi-quantitative data that can be derived from electric logs is in the nature of an operational bonus. Thus, we should recognize the fact that a purely academic approach to the problem of quantitative log interpretation is economically unjustified. If it can be shown that rigid and universal methods of log interpretations are not theoretically probable, we are still entitled to use the available theory to suggest such semi-empirical approximations as appear to be justified under certain specific conditions obtaining in certain limited geographical areas.

*** The recent experimental data of Dunlap, Bilharts, Shuler and Bailey[25] and Williams[26] appear very strongly to confirm this theoretical prediction.

The Estimation of Connate Water Saturation from Log Data

The use of electric logs for the qualitative location of oil or gas saturation in reservoir rock depends fundamentally on the derivation of three parameters. These parameters are the true formation resistivity, the resistivity of the connate water at the formation temperature and the true formation factor. It is believed that the first two parameters can now be obtained with a high degree of accuracy in many instances. The estimation of formation factor is less readily made. It is not only difficult to determine formation factor with accuracy from present log data, but the apparent value, when deduced from the log, may be increased by residual oil saturation and decreased by conducting solids.[8] If an oil-water contact exists, it is theoretically possible to correct the apparent formation factor for the effects of conductive solids.[9] If such a condition does not obtain, the best method (in the absence of cores) still appears that of assuming the formation factor to be identical with the formation factor of a water sand adjacent to the one of interest. New techniques for estimating formation factor in situ are thus of prime importance to log interpretation. However, from a strictly qualitative approach, it is clearly desirable to overestimate the numerical value of formation factor, since the qualitative identification of hydrocarbon saturation in a formation is based on the relationship:

$$F\rho_c \ll \rho_t$$

Where,

F = true formation factor,
ρ_c = connate water resistivity,
ρ_t = true formation resistivity (corrected for conducting solids).

From the standpoint of quantitative log interpretation, the above difficulties are reinforced by the additional difficulty of finding the appropriate value for the exponent, n, in the resistivity index-saturation relationship,

$$I = S_w^{-n} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Fig. 5 shows a plot of water saturations, S_w, against values of the exponent, n, for various constant values of the resistivity index, I. Each curve of the family plotted may be shown to have a slope given by the relationship $(\partial S_w/\partial n)_I = -S_w \ln S_w/n$, and all curves may be calculated from the appropriate value of $(\partial^2 S_w/\partial n^2)_I = 0$ to have a point of inflection at a saturation of 0.136 (13.6 per cent).

It is clear from Fig. 5 that if the exact value of n for a particular formation is unknown to the log interpreter, the maximum error in a water saturation computed by arbitrarily assuming a value for n will result for true water saturations of about 14 per cent. Fig. 5 shows, however, that although maximum errors in interpretations are to be anticipated at saturations in the region of 14 per cent, the errors at any other saturations in the saturation range applicable to producing formations are also extremely serious. For example, if the probable range of n values in commercial oil-bearing reservoirs is assumed to be from 1 to 4, a resistivity index of 10 may be seen from Fig. 5 to indicate saturations anywhere from 10 per cent to 56.5 per cent, i.e., that reservoir may be computed to be either a potential producer of pipe line oil or a potential water sand, unless a more specific value of n for the reservoir is either definitely known or can be reliably as-

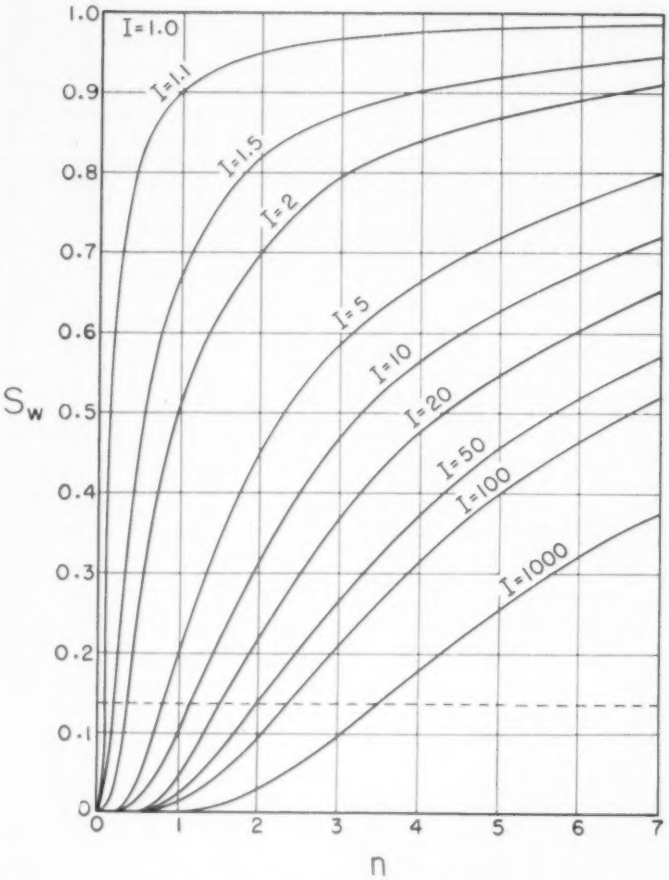

FIG. 5 — GRAPHICAL SOLUTION OF $I = S_w^{-n}$

sumed. However, Fig. 5 may be used to divide computed resistivity indices into three broad categories if the range of practical n values for all saturations is assumed to be from 1 to 4.

In the first category are resistivity indices less than 2. Such indices indicate water saturations in excess of 52 per cent and may almost invariably be assumed to be indicative of water sands.

In the second category are resistivity indices in the range 2-20. If possessed of such an index a formation may be either a pay sand or water producing since saturations may vary from 5 per cent to 84 per cent. Thus, in the absence of any information concerning the appropriate value of the exponent n to use, resistivity indices in this range give no reliable guide to production possibilities.

In the third category are resistivity indices which exceed 20. In this range the formations certainly contain less than 47 per cent water even for values of n as high as 4, and the probability of the formations containing oil or gas in commercial quantities is, in consequence, very high.

It appears probable from the theoretical treatment given above that the exponent n varies with the texture of the reservoir rock, the extent of wetting liquid saturation and other factors normally unknown to the log interpreter. While this conclusion requires further experimental elucidation, we do not consider that it is at present theoretically justifiable to regard the relation $I = S_w^{-n}$ as anything but a mathematical convenience. In practice, however, it would appear from the available experimental evidence that for reservoirs with low irreducible water saturations (in about the range 8 - 20 per cent) and probable variation of n may well lie within narrower limits than the range 1 to 4 previously discussed. For reservoirs with irreducible saturations from about 8 - 20 per cent, present experimental evidence indicates that n may only vary from about 1.7 to 2.5 in a large number of practical cases. If this is so, fairly reliable quantitative saturations may be calculated on the basis of the exponent $n \approx 2$, notwithstanding the fact shown above that in this saturation range errors in S_w arising from errors in n are at a maximum. Table III gives the saturations applicable to a number of resistivity indices for values of the exponent n of 1.7, 2.0 and 2.5.

Table III

n =	1.7	2.0	2.5
I	S_w	S_w	S_w
20	17.2	22.4	30.2
40	11.3	15.9	25.2
60	9.0	13.0	19.5
100	6.7	10.0	15.9

It will be seen that although the values of S_w in Table III differ considerably, an exponent of 2.0 would, nevertheless, give saturations of considerable utility to the reservoir engineer. If, in addition, it is recollected that no reservoir is texturally homogeneous or uniformly saturated, it is not unreasonable to believe that the intrinsic tendency of the log to yield average data for a large volume of reservoir rock may give rise to a computed saturation in excellent quantitative agreement with the mean of the irreducible water saturations obtained by core analysis techniques on a number of sample cores from the formation logged.

In the light both of available experimental data and theoretical considerations we would, however, strongly deprecate the attachment of undue importance to calculated numerical values of saturation in excess of about 30 per cent unless the textural constants of the reservior had previously been established.

The Estimation of Porosity From Log Data

From the theoretical section above it may be deduced that the porosity, ϕ, in Archie's relationship between porosity and formation factor and exponent, m, can be expressed as:

$$\phi = \frac{T^{1/2}}{F} = T^{\frac{1}{2(1-m)}} = F^{-\frac{1}{m}} \quad . \quad . \quad . \quad . \quad (13)$$

Assuming that formation factor is obtainable from purely log data, porosity can only be computed if a reasonably accurate value of m can also be derived from log data. Equation 13 emphasizes that this is possible only in the event that tortuosity is obtainable from log data. Since no method of deriving tortuosity from log data alone is apparent, we conclude that the quantitative determination of porosity from the electric log is not at present possible. The nature of the problem, as exemplified by Equation 13, suggests that the only feasible practical methods for determining porosity, which will not involve a full coring program, will depend upon the combination of log data with such core analysis data as can be obtained on cuttings or side wall samples.

Qualitatively, Fig. 1 reinforces graphically the prevailing view that low formation factors will always be associated with rather high porosities. Tortuosity cannot be less than unity, hence a formation factor of 10 will mean a porosity of at least 10 per cent. Similarly, a formation factor of 5 implies a porosity greater than 20 per cent.*

The Estimation of Permeability From Log Data

Tixier has recently published[2] a method of determining permeability from log data which he shows to be of practical utility in the Mid-continent area. An examination of Tixier's treatment indicates that a number of assumptions are inherent in his approach and that these assumptions appear unnecessarily to limit any wide application of his method. Fundamentally, Tixier assumes that the exponent in the resistivity index-saturation relationship is 2.0, and that at any saturation, S_w, capillary pressure, P_c, is related to permeability, K, in the manner,

$$P_c = \frac{\text{Constant}}{K^{1/2}}$$

On the basis of these two assumptions he derives an expression for formation permeability in terms of the densities of brine and hydrocarbons in a porous formation and the slope of the resistiv-

* The fact that for a constant formation factor, Fig. 1 shows tortuosity to increase with increase in porosity can be rationalized by recollecting that constancy of formation factor with increasing porosity is inherently improbable in any real porous medium.

ity curve above the oil-water contact. Tixier's method is physically limited in scope by the relative paucity of logs showing valid oil-water contacts and the necessity for estimating the hydrocarbon density as it exists in the reservoir. More fundamentally however, the equation connecting capillary pressure and permeability at any saturation appears to us to represent a simplification which is in most cases quite unreal. The assumption regarding the value of n, with the reservations we have outlined above, we consider to be more justified.

Leverett has developed in two of his theoretical papers[20,22] a relationship for porous solids which may conveniently be expressed in the following form:

$$P_c = \left(\frac{\phi}{K}\right)^{1/2} j(S_w)\ \delta \cos\theta \quad . \quad (14)$$

where P_c, ϕ and K have the same significance as before, δ is the interfacial tension, θ the contact angle, solid to liquid, of the wetting phase, and $j(S_w)$ is Leverett's capillary pressure function. From this equation the relationship between capillary pressure and permeability employed by Tixier follows, if ϕ, $j(S_w)$, δ and Cos θ are identical, or mutually compensating in their effects, in all the formations he studied. The universal constancy of δ Cos θ in water-wet oil field reservoirs is only acceptable as a first approximation, since it would seem that surface-active components of some crudes might markedly affect the interfacial surface tension. Wide variations in porosity are clearly to be expected, although in an area such as the Rocky Mountains a relatively constant porosity may have obtained. Independent values for the capillary pressure function at various saturations are unobtainable at present, although the value of $\lim_{S_w \to 1} j(S_w)$ has been shown by Rose and Bruce[20] to be equal to $(1/t)^{1/2}$, where t is the Kozeny rock textural constant. At any saturation, however, $j(S_w)$ is a function of the rock textural character of the formation and, hence, it may have wide variations not only from reservoir to reservoir but within any particular formation. Thus, the constant employed by Tixier, as Tixier noted, is certainly liable to vary very widely in different reservoirs and even in a particular area its constancy does not seem to be probable except in very ideal circumstances. It would appear from Tixier's results that the formations to which he applied his method were singularly texturally homogeneous and, thus, perhaps uniquely amenable to his treatment.

Since Leverett's equation indicates the factors which will affect Tixier's empirical "constant", it is reasonable to examine the possibilities of being able to express these factors in terms of measurable log data and thus to derive an expression of somewhat wider applicability.

Rose and Bruce[20] have shown that when S_w is unity,

$$P_d = \left(\frac{1}{K}\right)^{1/2} \delta \left(\frac{\phi}{t}\right)^{1/2}$$

(Contact angle assumed to be 0) But it has been shown in the theoretical section that, $F = t^{1/2}/t_c^{1/2}\phi$. Hence,

$$P_d = \delta/(Kt_c\phi)^{1/2}\ F \quad . \quad (7)$$

The displacement pressure, P_d, does not seem to be obtainable from the electric log, but P_c may be derived in principle by using the same technique as that employed by Tixier. The gen-

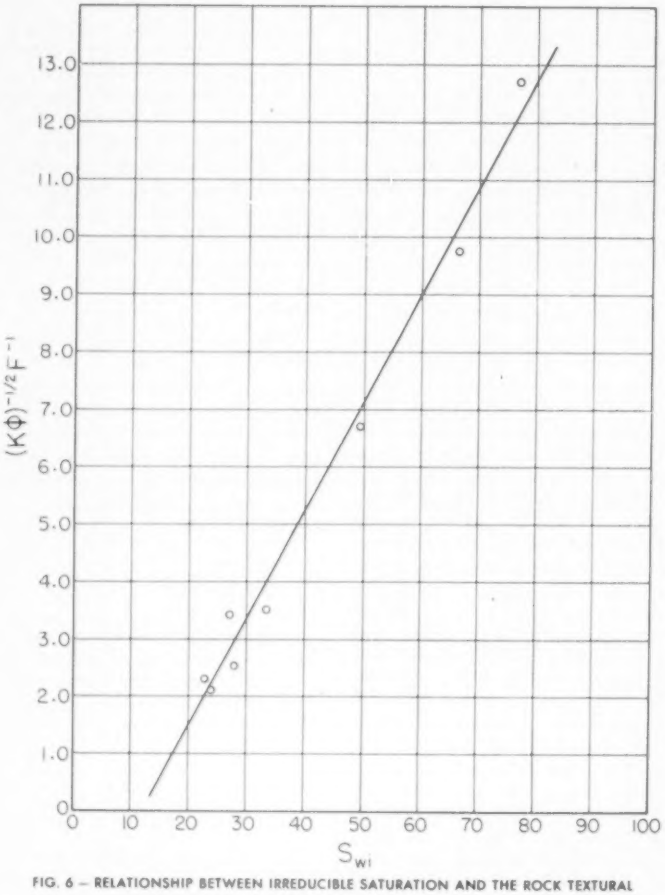

FIG. 6 – RELATIONSHIP BETWEEN IRREDUCIBLE SATURATION AND THE ROCK TEXTURAL FUNCTION $(K\ \phi)^{-1/2}F^{-1}$

eral relationship between P_c and P_d for all porous media undoubtedly is complex, but to a first approximation the relationship derived by Rose and Wyllie[20] may be used. This relationship states that $P_d = P_c S_w^{1/2}$. It then follows that,

$$P_c = \left(\frac{1}{K}\right)^{1/2} \frac{\delta}{Ft_s^{1/2}\phi^{1/2}S_w^{1/2}}$$

or that,

$$K = \frac{\delta^2}{P_c^2 F^2 t_s \phi S_w} \quad . \quad . \quad . \quad (15)$$

In Equation 15 δ may be assumed constant, to a first approximation, and since t_s varies from about 2.0 to 2.5, it also is essentially a constant. The porosity, ϕ, is not calculable from log data directly, but by assuming a reasonable value for m in the expression $F = \phi^{-m}$, ϕ may be expressed in terms of F with an accuracy compatible with the other practically essential approximations. Thus, in terms of parameters which are obtainable from appropriate logs,

$$K = \text{Constant} \left[\frac{1}{P_c^2 F^{\left(2-\frac{1}{m}\right)} S_w}\right]$$

where the constant is $\frac{21.2\,\delta^2}{t_s}$. (16)

for K in millidarcies, P_c in psi and δ in dynes/cm. In this expression, in the absence of other knowledge, a value of $m = 1.5$ is convenient. The constant, since it is dependent only on δ, θ and t_s may well have rather wide applicability unless variations in δ are in fact very large.** The value of K deduced from this equation cannot, however, be expected to have more than an order of magnitude significance.

Our prime objection to the use of Tixier's method or the generalization of it outlined above, lies in the practical consideration that insufficient logs showing suitable oil-water contacts are obtained. Another inherent objection is the knowledge of the hydrocarbon density in situ which is required and which makes the method not immediately applicable when working in unknown territory. We have thus examined the possibility of devising a method of computing permeability under conditions where no oil-water contact exists and where no knowledge of the reservoir hydrocarbons has been obtained. With these severe limitations the problem becomes that of finding a relationship between permeability, formation factor and connate water saturation, since only the two latter quantities appear in principle to be calculable from log data. We make, in addition, the further assumption that the minimum water saturation computed in a reservoir is equal to the irreducible connate water saturation, S_{wi}. In this we follow the basic assumption of all capillary pressure core analysis.

The sole justification for attempting to connect permeability to irreducible water saturation and to formation factor lies in the probability that all three parameters are functions of rock texture. It is well-known that in rocks of similar texture, i.e., from the same reservoir, there is frequently a definite relationship between irreducible saturation and permeability. However, the permeability for the same irreducible saturation may differ by several orders of magnitude if the rock texture changes. In order to obtain a general expression which will give permeability

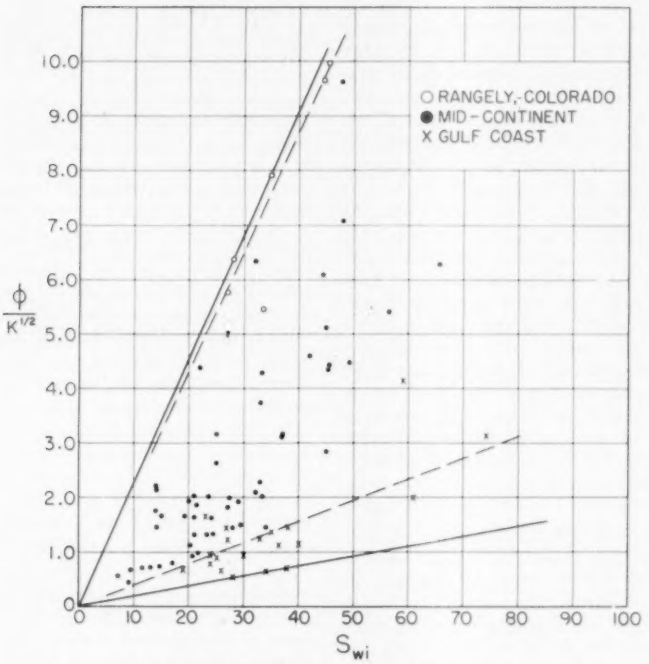

FIG. 7 — EMPIRICAL RELATIONSHIP BETWEEN IRREDUCIBLE SATURATION AND THE ROCK TEXTURAL FUNCTION $\phi/K^{1/2}$

** From the logs published in Tixier's paper[2] the following approximate data may be derived. Formation factors are computed from the true resistivities of the water sands and the stated connate water salinities using temperatures appropriate to the depths shown.

Log	F	S_w	P_c psi	K(lab)md	Computed δ dynes/cm
Layton, Oklahoma	10	0.33	6.7	27	30.2
Cisco, North Texas	16	0.315	4.7	200-700	76.5-143
Tensleep, Wyoming	7	0.35	1	450	14.9
Rangely, Colorado	50	0.37	18.5	2.72	79.5

The values for interfacial tension are computed by solving for δ in Equation 16, m assumed 1.5 and n as 2 in every case. It will be seen that the values for δ so obtained are extremely variable and rather high. Errors in the assumed m are insufficient to reduce significantly the high computed values of δ, particularly as the high values of δ are associated with high formation factors. The fact that S_w appears to be independent of K points also to errors in n since the computed values of δ are directly proportion to $S_w^{1/2}$.

(or at least its order of magnitude) in terms of S_{w_i} and F, it follows that F must appear in the desired expression in such a manner as to compensate these rock textural variations.

With these considerations in mind we have approached the problem in the following manner. Rose and Bruce[20] have discussed the application of the Kozeny equation for the estimation of interstitial surface areas and have found a reasonably linear relationship when surface area is plotted against irreducible connate water determined by the capillary pressure method.*** Now the Kozeny equation giving interstitial surface area, A, per unit of pore volume is:

$$A = \left(\frac{\phi}{K}\right)^{1/2}\left(\frac{1}{t}\right)^{1/2}$$

$$= \frac{1}{K^{1/2}\phi^{1/2}Ft_s^{1/2}}, \quad \text{substituting for } t = Ft_s\phi^2$$

If the assumption is made that m=1.5, $\phi^{1/2}$ may be expressed as $(1/F)^{0.33}$ whence,

$$A = \frac{1}{1.5K^{1/2}F^{0.67}}, \quad \text{since } t_s \cong 2.25$$

If S_{w_i} is a straight line function of A, then we have,

$$S_{w_i} = C\left[\frac{1}{K^{1/2}F^{0.67}}\right] + C' \quad . \quad (17)$$

where, C is a constant which must have the dimensions of a length, and C' is a dimensionless constant.

In a clean sand, S_{w_i} is zero when the interstitial surface area is zero. Thus, for clean sands, i.e., with no interstitial water held in clays, the straight line must pass through the origin and C' = 0. Fig. 6 shows some data we have for a producing zone in a Californian field. In this figure S_{w_i} has been plotted against $(1/K^{1/2}\phi^{1/2}F)$, no assumption being made regarding the value for m. The formation factors of the sands, all of which contained clay, were obtained with a fluid sufficiently saline to give good values of F.* It will be seen that the points fall on a moderately good straight line and that the value for the constant C' is about 12 per cent water.

The present dearth of data suitable for testing Equation 17 results from the scarcity of formation factor values, not from lack of determinations of permeability, porosity and irreducible saturations. However, as an approximation Equation 17 can be written in the form,

$$S_{w_i} = C \cdot \frac{\phi}{K^{1/2}} + C' \quad . \quad . \quad (18)$$

if, $F = \phi^{-1.5}$ is assumed to hold in all cases. This form of the equation is likely to be considerably less accurate than that involving F, since the effect of the assumption concerning the value of m assumes greater importance.‡‡ However, there are sufficient available data for Equation 18 to be used to test the approximate general validity of Equation 17, i.e., whether the constant which relates irreducible saturation to interstitial surface area is markedly dependent upon rock texture, or whether some mean value could be assumed for all types of formation. In the latter event it would be simple to set up curves giving a mean or minimum value for permeability in terms of the formation factor and irreducible saturation of any reservoir. It should be noted that Fig. 6 indicates that dirty formations are unlikely to fit this picture, since they may have an irreducible water saturation corresponding to an interstitial surface area of zero.

Fig. 7 shows a plot of S_{w_i} against the function per cent porosity/(permeability in millidarcies)$^{1/2}$ for 80 determinations. The data for the Mid-continent are mean values of S_{w_i}, porosity and permeability made on intergranular-type cores (including oolitic) from reservoirs in Kentucky, Illinois, Oklahoma and Texas. A few points refer to similar data on cores from California fields. It will be seen that while the scatter of points is considerable, the data for Rangely, Colorado, (given by Rose and Bruce[20]) tend to fall on a straight line passing through the origin. These points also define the minimum value of permeability for a given porosity. Conversely, Thornton and Marshall's data[22] which refer to a Louisiana Gulf Coast reservoir of Miocene Age, tend to fall about another line passing through the origin and correspond to maximum permeabilities at any given porosity. The Mid-continent and California data fall between these two extremes.

Fig. 7 in itself does not lend support to the hope that a reasonably accurate general constant can be found to express the relationship between S_{w_i} and $\phi/K^{1/2}$. Fig. 7 shows, in fact, that for any given saturation and porosity the maximum possible permeability may be 150 times as great as the minimum possible permeability. It must be remembered, however, that Fig. 7 is greatly dependent upon the assumed value for the exponent m and, as shown above, the scatter is also likely to be considerably influenced by interstitial clay in the formations considered.

The data for the Mid-continent and California show a ratio of 22 between maximum and minimum values of permeability for any given porosity, and there is a probability of about 0.9 that under the same conditions the ratio between maximum and minimum permeabilities will not exceed 12. In general, it seems possible that plots similar to Fig. 7 but involving formation factor, may have some merit for the determination of the order of magnitude of permeabilities over quite wide ranges of formation texture. It also seems theoretically possible that when more data are available the constant C in Equation 17 may be expressible in terms of other formation texture parameters, in which case a unique curve relating all formations would be obtained. It may be mentioned that a constant C of the form $\phi^3/(1-\phi)^2$ serves markedly to reduce the scatter between the Rangely, Colorado data points and those of Thornton and Marshall, but does not consistently improve the Mid-Continent and California data. The term $\phi^3/(1-\phi)^2$ is the porosity function which appears in the Kozeny equation when the specific surface area is expressed in units of grain volume. Carman[21] shows that $\phi^3/(1-\phi)^2$ is that measure of rock texture which relates permeability to average grain diameter.

*** It is as well to note that this relationship is clearly not applicable to the elementary case of packed homogeneous spheres, since here A is a function of both sphere radius and porosity, whereas S_{w_i} is independent of sphere radius. However, in consolidated porous media some relationship between A and S_{w_i} is more plausible.

‡‡ It may be noted that Equation 18 implies that $\phi = 1/t$, an equality not often encountered in practical cases and indicative of the errors involved in assuming a constant m=1.5.

SUMMARY AND CONCLUSIONS

In this paper we have had as our principal object the investigation of the inherent probabilities of deriving reliable information regarding the physical characteristics of reservoir rock from electrical log data. We have indicated that since electric logs are now an almost universal aid to well completion any information of a quantitative character which can be derived from electric logs is in the nature of a gift. It may also be pointed out that the value of this gift would be considerably enhanced if it led also to a curtailing or elimination of present coring and core analysis techniques.

Our analysis of the problem has enabled us to give physical interpretation to the significance of such logging parameters as cementation factor, formation factor and resistivity index exponent, and we have shown that these logging parameters are related to the rock textural parameters appearing in the Kozeny equation and expressions of capillary pressure phenomena. Our conclusions, from a strictly theoretical standpoint, do not, however, suggest that accurate estimates of reservoir rock parameters may presently be made from electrical log data alone, although possibilities exist that the judicious combination of log data and selected core analysis data may often give expressions for certain of these parameters which have fairly wide applicability.

Specifically we have derived, on the assumption that the tortuosity, T, applicable to fluid flow of the wetting phase in a porous medium is the same as the tortuosity affecting electrical conductivity through the fluid in the same medium, an expression for formation factor, F, of the form, $F = T^{1/2}/\phi$, where ϕ is the porosity of the medium. From this expression, we have shown that the common relationship $F = \phi^{-m}$ is of no fundamental significance and have indicated why the practical limits of m are likely to be from 1.3 to 3.0. We have also shown that the existence of reservoirs where a constant value of m will obtain, irrespective of porosity, is not to be anticipated. Experimental evidence for the formation factor relationship derived is also presented.

Applying the same assumption regarding the equality of the hydraulic and electrical tortuosities of the wetting phase in partially saturated porous media, e.g., brine-oil systems, we have derived an expression for the resistivity index, I, in terms of saturation and the ratio of the wetting liquid tortuosities at 100 per cent saturation and the saturation, S_w, considered. Thus, $I = (T_r/T)^{1/2} S_w$.

We show that the use of this expression leads to the conclusion that the resistivity index exponent n in the relationship $I = S_w^{-n}$ is dependent on the texture of the porous medium and the wetting liquid saturation. Thus, it appears that n is neither universally constant at a value of about 2 in all porous media, nor is it necessarily constant throughout the whole saturation range in any particular porous medium. However, both available experimental data and theoretical considerations appear to indicate that at low wetting phase saturations n may lie between 1.7 and 2.5 in a large number of practical instances, and thus a value of $n = 2$ has considerable practical utility.

We show that the accurate determination of porosity from log data alone is not possible, although limits to the porosity may be given. Thus, a formation factor of 5 implies a porosity in excess of 20 per cent, while one of 10 implies a porosity of at least 10 per cent.

We have expanded an empirical relationship proposed by Tixier and show that the order of magnitude of a formation permeability, K, may be obtained from the relationship:

$$K = \text{Constant} \left[\frac{1}{P_c^2 F^{\left(2-\frac{1}{m}\right)} S_w} \right]$$

where the constant is equal to $\frac{21.2\,\delta^2}{t_r}$ for K in millidarcies, capillary pressure, P_c, in psi and interfacial tension, δ, in dynes/cm. The value for t_r lies between 2.0 and 2.5 and may be taken as 2.25.

In order to obtain an estimate of permeability when P_c is unobtainable (i.e., in the absence of an oil-water contact in the reservoir) we suggest a correlation between irreducible saturation, S_{w_i}, permeability and formation factor of the form:

$$S_{w_i} = C \left[\frac{1}{K^{1/2} F^{m/2}} \right] + C'$$

where C and C' are constants.

Evidence from a number of oil reservoirs in the United States is given to substantiate this type of correlation.

ACKNOWLEDGMENTS

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NOMENCLATURE

A	Specific surface area of pores per unit of pore volume.
A_c	Area of face of core.
C	Textural constant with the dimensions of a length connecting irreducible water saturation to permeability and formation factor.
C'	Dimensionless constant.
F	True formation factor of porous solid.
F_e	Effective true formation factor of a porous system partially saturated with a non-conducting non-wetting phase.
F_r	Hydraulic formation factor.
I	Resistivity index.
$j(S_w)$	Capillary pressure function.
K	Specific permeability.
K_{rw}	Relative permeability to wetting phase.
L	Actual length of core.
L_e	Mean effective length of pores in core.
m	Cementation factor exponent.
n	Saturation or resistivity index exponent.
N	Number of pores in any cross section A_c.
P_c	Capillary pressure.
P_d	Displacement pressure.
R	Radius of hypothetical cylindrical core of area A_c.
r	Pore radius.

S_w Fractional wetting phase saturation.

S_{wi} Fractional "irreducible" wetting phase saturation.

t Kozeny rock textural constant.

t_s Pore shape factor.

T Tortuosity $= (L_e/L)^2$.

T_w Effective tortuosity at any saturation of the wetting phase.

δ Interfacial tension.

ϕ Fractional porosity.

μ Fluid viscosity.

ρ_e Interstitial water resistivity.

ρ_t True core or formation resistivity.

ρ_w True resistivity of a core or formation 100 per cent saturated with a conducting wetting phase.

θ Contact angle, solid to liquid, of the wetting phase.

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THE COEXISTENCE OF LIQUID AND VAPOR PHASES AT PRESSURES ABOVE 10,000 PSI

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ABSTRACT

With greater effort being devoted to the discovery of new oil and gas reserves and a consequent increase in bottom hole pressures due to greater drilling depths, the phase relationships of hydrocarbon fluids at pressures above 10,000 lb psi are becoming increasingly important.

The present paper discusses the results of research with a windowed cell on a methane-Kensol 16 system to pressures of 25,000 lb psi and temperatures to 260°F. Kensol 16 is a commercial high narrow-boiling-range oil. It is shown that for the temperature range of 60°F to 260°F, this particular system exists in two phases to pressures of approximately 14,000 lb psi, and data are presented giving the relative amounts of liquid and vapor phases coexisting under these conditions. Partial phase diagrams are shown for six different mixtures of methane and Kensol 16, three of which include the critical region.

In contrast to mixtures composed of substances of fairly close volatility, critical opalescence was noted for as much as ±200°F of the critical temperature.

The critical locus of the methane-Kensol 16 system was estimated and the conventional pressure-composition and temperature-composition diagrams were prepared. From these, the equilibrium vaporization factors for methane and Kensol 16 were estimated for temperatures from 60°F to 700°F and to pressures above 12,000 lb psi.

The relations of this study to petroleum production problems and other phase equilibria research are discussed.

[1] References given at end of paper.

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INTRODUCTION

A knowledge of the physical behavior of naturally-occurring hydrocarbon mixtures is fundamental to a thorough treatment of nearly all operations involved in the recovery, refining, and transportation of petroleum. The operations may involve the applications of phase relationships, and the relative

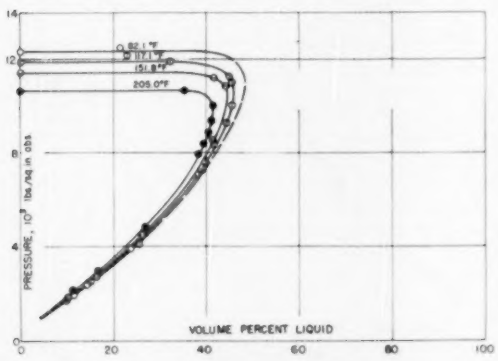

FIG. 1 — VOLUME PER CENT LIQUID 52.00 WT. PER CENT METHANE

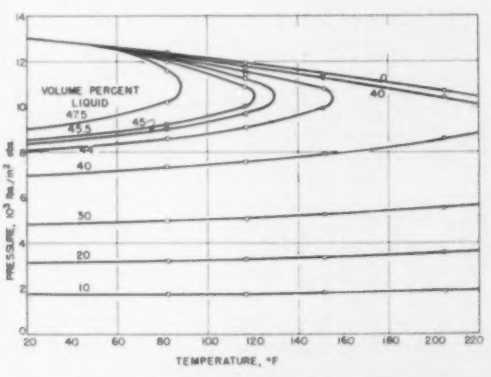

FIG. 2 — PHASE DIAGRAM 52.00 WT. PER CENT METHANE

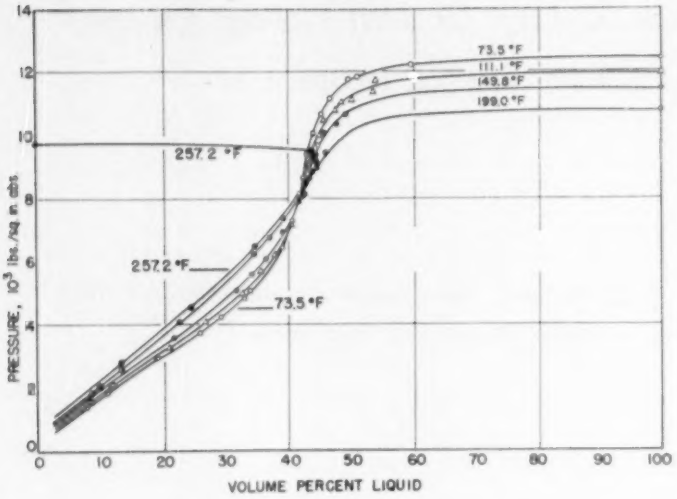

FIG. 3 — VOLUME PER CENT LIQUID 49.8 WT. PER CENT METHANE

amounts and compositions of phases coexisting at various pressures and temperatures.

The phase relationships of pure hydrocarbons are well understood. Binary systems containing methane have been studied from 60°F to 460°F and pressures to 10,000 lb psi.[1,3,5,9,11,13-17,19,24-26] No two-phase pressures in binary systems above about 5,300 lb psi have been studied. Several ternary[6,7,23] and complex systems[12,14,21,22,27,28] have been investigated. Two-phase pressures for a natural gas-crude oil system up to 10,000 lb psi have been studied by Roland.[21] Indications that two phases may exist at pressures to 25,000 lb psi were anticipated by Katz and Singleterry.[13] However, no cases have been reported where two phases were actually found to exist at pressures above 10,000 lb psi.

There have been recent indications that oil and gas pools having formation pressures approaching 10,000 lb psi are being discovered and exploited. It is entirely conceivable that reservoir pressures above 10,000 lb psi may become common in the near future, and it was with the idea of investigating phase relationships of hydrocarbon systems above this pressure that the present research was undertaken.

EQUIPMENT AND MATERIALS

The results presented in this paper were obtained with a high pressure cell containing ten windows which could be used for visual observations of phase phenomena occurring to pressures of 25,000 lb psi and temperatures to 300°F.[21]

The methane used in the present investigation had been furnished by the Phillips Petroleum Co. to Bicher for his study of the methane-propane viscosities.[2] The methane was guaranteed to have a minimum purity of 99.0 mol. per cent and was further purified by passing it through a train of tubes containing ascarite, activated charcoal, and granular calcium chloride.

Kensol 16 is a commercial narrow-boiling-range oil, two gallons of which were supplied gratis by the Kendall Refining Co. It had an initial boiling point of 567°F, midpoint of 574°F, and an endpoint of 589°F, and an experimentally determined molecular weight of 246.9.

EXPERIMENTAL RESULTS AND DISCUSSION

Nineteen different compositions of methane-Kensol 16 mixtures were in-

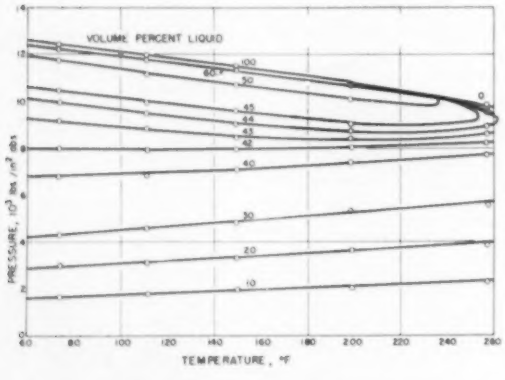

FIG. 4 — PHASE DIAGRAM 49.80 WT. PER CENT METHANE

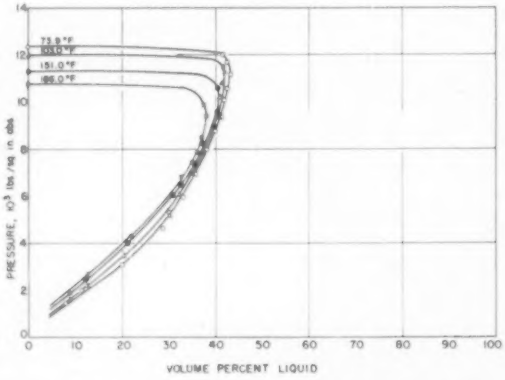

FIG. 5 — VOLUME PER CENT LIQUID 55.45 WT. PER CENT METHANE

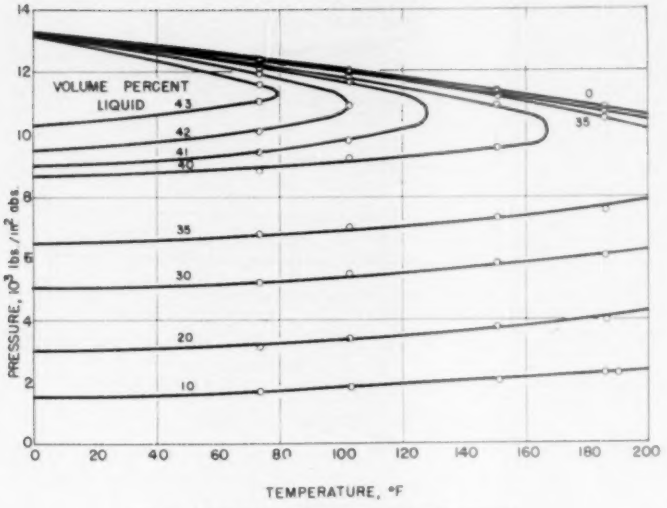

FIG. 6 — PHASE DIAGRAM 55.45 WT. PER CENT METHANE

vestigated during a series of 52 runs. The data obtained included densities of the entire system, saturation pressures, volume per cent liquid at various pressures and temperatures, and all accessory information on critical opalescence and that necessary for computing the compressibility factors.

Critical Opalescence

Critical opalescence was observed in all mixtures whose compositions varied between 45 and 55 weight per cent methane. Three mixtures, composed of 15.78, 72.70, and 75.78 weight per cent methane respectively, did not exhibit critical opalescence. Kurata and Katz[11] found that this color phenomenon occurred within a temperature range of ±50°F of the critical temperature for mixtures of volatile hydrocarbons such as natural gas and natural gasoline. In the present research, the color phenom-

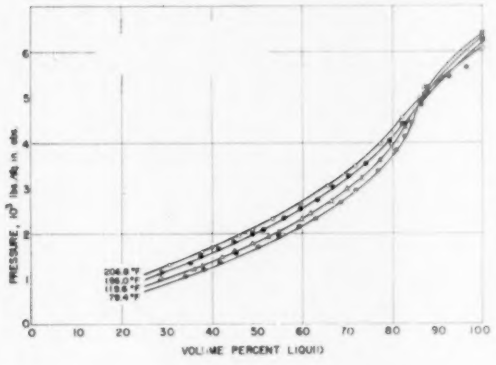

FIG. 7 — VOLUME PER CENT LIQUID 15.78 WT. PER CENT METHANE

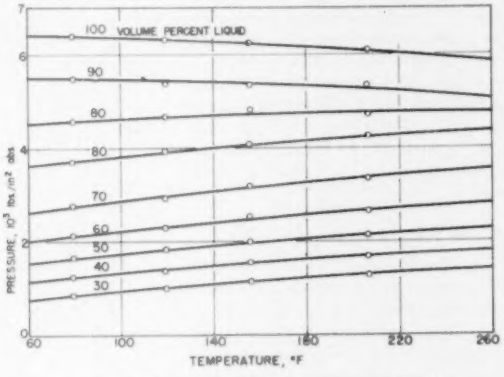

FIG. 8 — PHASE DIAGRAM 15.78 WT. PER CENT METHANE

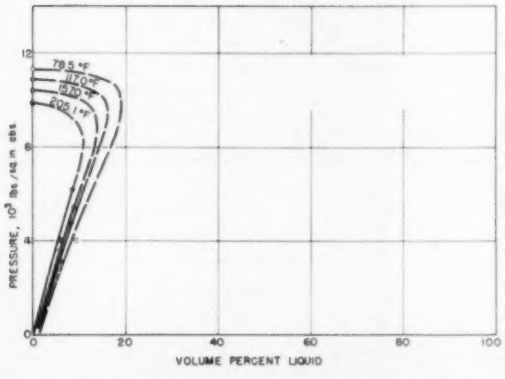

FIG. 9 — VOLUME PER CENT LIQUID 75.74 WT. PER CENT METHANE

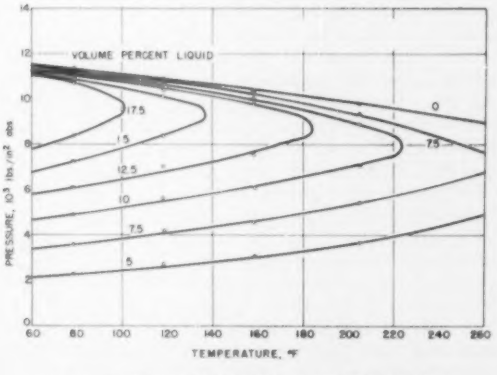

FIG. 10 — PHASE DIAGRAM 75.74 WT. PER CENT METHANE

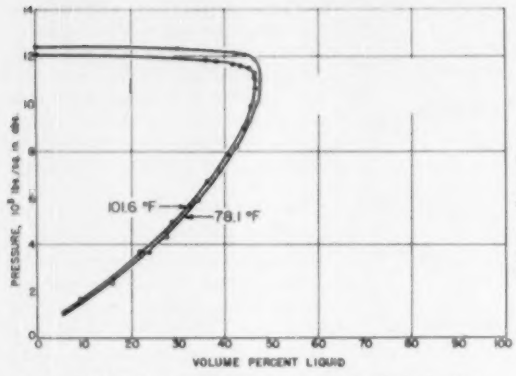

FIG. 11 — VOLUME PER CENT LIQUID 52.10 WT. PER CENT METHANE

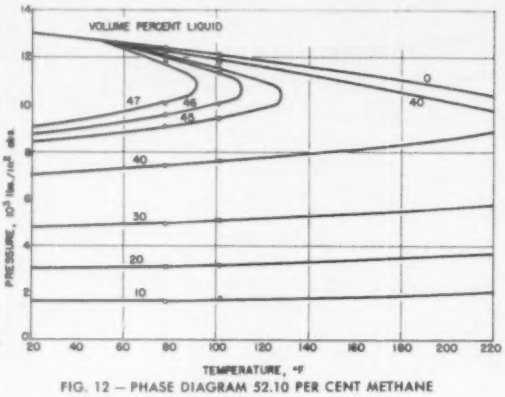

FIG. 12 — PHASE DIAGRAM 52.10 PER CENT METHANE

ena were definitely discernible over the entire range of temperatures investigated. This would indicate that the critical opalescence occurs over a wider temperature spread when the volatility spread between components comprising the system is increased.

As in the case of Kurata and Katz,[16] the mixtures appeared cherry-red to brown-red by transmitted light and blue-green by reflected light. Critical opalescence is believed to be caused by the association of molecules into tiny droplets of the liquid phase or bubbles of the vapor phase, which is about to appear.[11,28,35,43]

Phase Diagrams

Perhaps the most reliable method of determining experimentally the critical temperature and pressure of a hydrocarbon mixture is to plot a phase diagram of the constant-composition mixture from experimental liquid volume per cent data. These data are first plotted as volume per cent liquid versus pressure for the isotherms investigated, as shown in Fig. 1, 3, 5, 7, 9, and 11. Such graphs are then cross-plotted to give the conventional pressure-temperature diagram showing lines of constant volume per cent of liquid. These lines are extrapolated to a common point on the boundary curve, and this common point is the critical point of the mixture in question.

Fig. 1, 3, 5, 7, 9, 11 show the experimental liquid volume per cent data for six mixtures of methane and Kensol 16, while Fig. 2, 4, 6, 8, 10, 12 show these data cross-plotted to give the phase diagrams or the pressure-temperature projections.

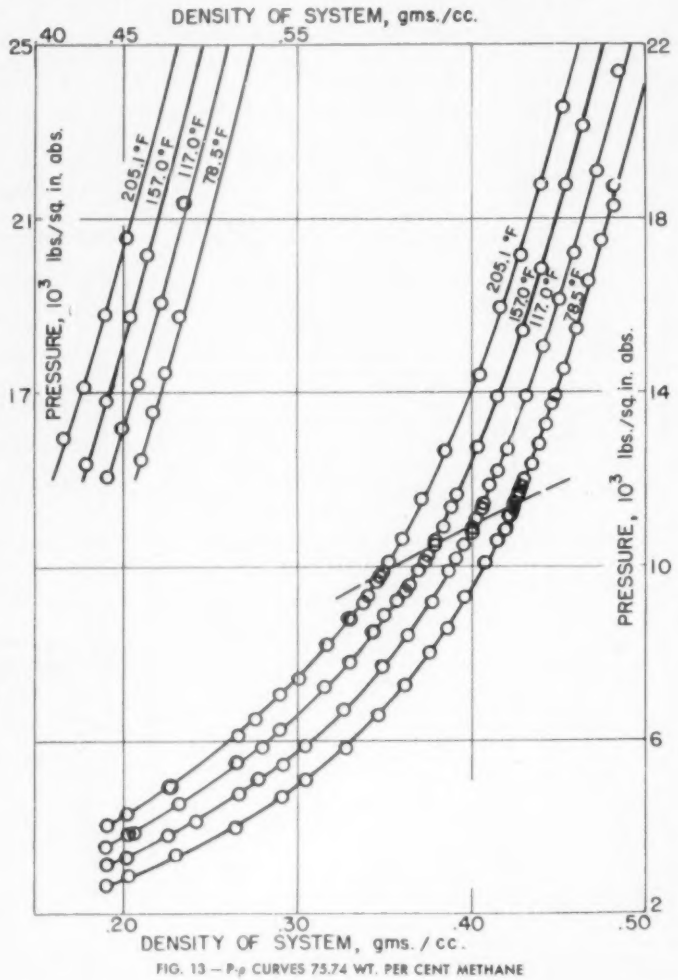

FIG. 13 — P-ρ CURVES 75.74 WT. PER CENT METHANE

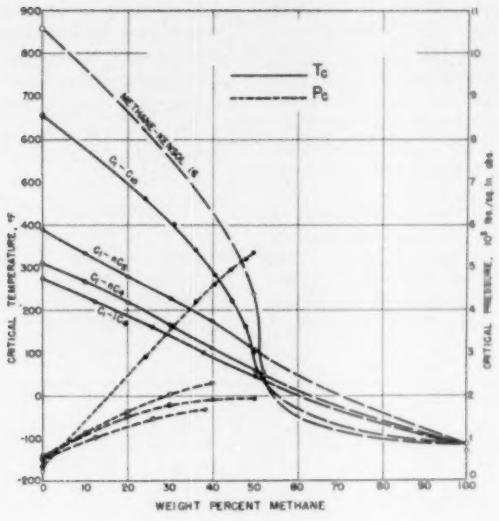

FIG. 14 — T_c AND P_c OF BINARY SYSTEMS

Experimental determinations of bubble points are quite frequently obtained from the break in the pressure-volume curves of the particular mixture studied. The present investigation stresses the difficulty in many instances of using this method in obtaining bubble or dew points. Fig. 13 shows experimental pressure-density isotherms for the mixture containing 75.74 weight per cent methane, the critical temperature of which was estimated to be −97°F. This mixture did not exhibit critical opalescence, so that it can be safely assumed that the actual critical temperature is fairly well removed from the experimental temperatures. Nevertheless, it can be seen from Fig. 13 that without visual means it would be very difficult, if not impossible, to determine the saturation pressure graphically. A pressure decrement of only a few pounds might result in complete "skipping over" of the break in the curve. This points out the fact that the visual method is perhaps the most reliable method of determining bubble points and upper dew points, even at temperatures well removed from the true critical temperature of the mixture.

Critical Properties

Only one mixture was investigated wherein the critical temperature was actually bracketed by the experimental isotherms. Limitations of the windows prevented the attainment of more isotherms and closer bracketing of the true critical temperature. The above-mentioned mixture contained 49.80 weight per cent, or 93.85 mol. per cent methane. By extrapolating the quality lines to a common point on the boundary curve, the critical temperature of this mixture was estimated as 235± 5°F, the critical pressure as 10,200± 100 lb psi absolute, and the critical density, as read from a pressure-density plot, was estimated as 0.458 grams per cubic centimeter.

Two other mixtures, one containing 52.00 weight per cent methane and the other 52.10 weight per cent methane, had their critical points close enough to the experimental isotherms to permit fair estimations of their critical points. The mixture of 52.00 weight per cent methane has a critical tempera-

Table I

Equilibrium Vaporization Factors as Computed From Fig. 15, 16 and 17

Pressure, psia	Temperature, °F	Equilibrium Factors	
		Methane	Kensol 16
2000	700	1.255	0.561
	600	1.628	.2195
	500	1.942	.0945
	400	2.160	.0398
	300	2.240	.0119
	200	2.255	.000585
	100	2.258	
	0	2.035	
4000	600	1.116	0.605
	500	1.350	.1918
	400	1.478	.0725
	300	1.543	.0200
	200	1.600	.00175
	100	1.620	
	0	1.595	
7000	400	1.100	0.364
	300	1.216	.073
	200	1.280	.0113
	100	1.302	.00252
	0	1.285	.00326
11,000	150	1.076	0.3065
	100	1.120	.1544
	0	1.152	.0848
12,000	100	1.035	0.597
	50	1.079	.3075
	0	1.089	.259

ture and pressure of 55±2°F, and 12,670±100 lb psi absolute, respectively. The mixture of 52.10 weight per cent methane has an estimated critical temperature, pressure, and density of 51±2°F, 12,700±100 lb psi absolute, and 0.545 grams per cubic centimeter, respectively.

The compositions investigated for critical properties were limited to a narrow range of weight per cent methane. It was discovered early in the research that the mixtures whose critical temperatures were between 60°F and 260°F or within the temperature range of this investigation, would probably have a composition of 50±1 weight per cent methane. This necessitated careful preparation of mixtures in order to bracket the critical temperatures.

Fig. 14 shows the critical temperatures and critical pressures of several binary mixtures containing methane plotted versus weight per cent methane. All the curves of critical temperature versus weight per cent methane exhibit inflection points at approximately 50 weight per cent methane, with the inflection becoming more marked as the molecular weight of the heavier hydrocarbon increases. The methane-decane system studied by Sage and Lacey[10] shows this inflection quite markedly. For a small change in composition in the vicinity of 50 weight per cent methane, the critical temperature of the methane-decane system exhibits a wide variation, from 217°F at 45 weight per cent methane to 80°F at 50 weight per cent methane. The same characteristics to a much greater degree were observed with the methane-Kensol 16 system, where the critical temperature varied from 235°F at 49.8 weight per cent methane to 51°F at 52.1 weight per cent methane. The estimated critical temperature locus for the methane-Kensol 16 system has been plotted in Fig. 14 for comparison.

The critical temperature and pressure for methane are −116°F and 673 lb psi absolute, respectively. From the specific gravity and molecular weight of the Kensol 16, its critical temperature and pressure were estimated as 859°F and 216 lb psi, respectively, by the method of Smith and Watson.[11] These values served as anchor points in plotting the critical locus of the methane-Kensol 16 system, as shown in Fig. 15.

Not all the points shown in Fig. 15 are experimental and many of them were obtained from the pressure-composition diagram of Fig. 16, which shows the experimental bubble and dew points plotted between the temperature range of 70°F to 260°F. Thus the shapes of the phase diagrams of Fig. 15 below 70°F and above 260° are estimated and open to question, but within the above temperature range, the curves are believed to be accurate to ±1.5 per cent.

Fig. 17 shows the conventional temperature-composition diagram for the methane-Kensol 16 system. Fig. 15, 16, 17 should be, and are consistent with each other and constitute the conventional pressure-temperature, pressure-composition, and temperature-composition plots.

As mentioned previously and seen from Fig. 14, the methane-Kensol 16 mixtures whose critical temperatures were between 70°F and 260°F were quite sensitive to composition changes. Fig. 18 shows the critical loci of binary

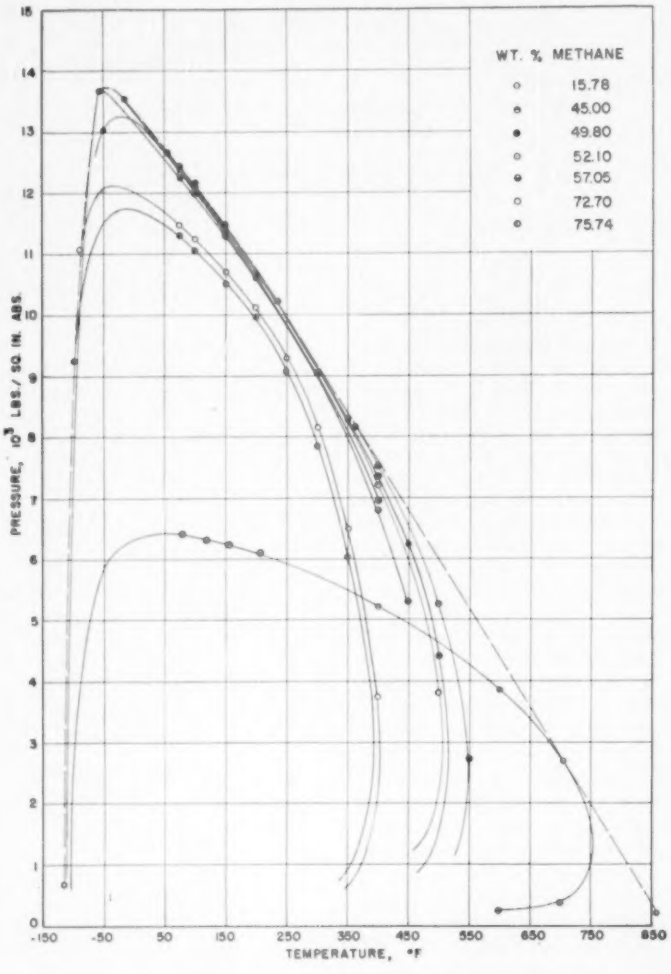

FIG. 15 — CRITICAL LOCUS OF METHANE-KENSOL 16 SYSTEM

hydrocarbon systems containing methane. Systems through the methane-hexane system exhibit fairly symmetrical critical loci curves. The methane-decane system shows a decided shifting of the maximum pressure toward methane. The methane-Kensol 16 exhibits similar reactions with the maximum critical locus pressure occurring at very high concentrations of methane, of the order of 56 weight per cent, or 95.14 mol per cent methane. Results on binary systems of carbon dioxide with propane, n-butane and n-pentane as investigated by Poettmann and Katz,[15] also indicate that the maximum pressure point on the critical loci curves shifts more and more toward the compound of higher volatility as the spread between the volatilities increases. For instance, the maximum pressure point of the carbon dioxide-butane system occurs at a composition of about 71 mol per cent carbon dioxide, and that of the carbon dioxide-pentane system at about 79.4 mol per cent carbon dioxide. Similar trends were observed in the carbon monoxide-propane system investigated by Widdoes and Katz[16] with the maximum pressure point occurring at about 90 mol per cent carbon monoxide.

The above discussion leads to a general conclusion: namely, that the greater the spread in the volatility of compounds comprising a binary system, the greater will be the deviation of the critical locus from symmetry, and the more will the critical locus curve be shifted toward the compound of highest volatility; the point of maximum pressure will occur at high percentages of the more volatile compound.

The assumption has almost always been made that the critical temperature of binary mixtures composed of pure substances or complex mixtures composed of various proportions of separator gas and liquid, would lie between the critical temperatures of the pure substances or of the separator gas and coexistent liquid. Recent work by Eilerts, et al.,[5] showed that it was possible to have the critical temperature of a complete system below the critical temperature of the more volatile component or fraction of that system. If the critical locus of the methane-Kensol 16 system is drawn between the critical temperatures of methane and Kensol 16, the critical locus curve will have a very sharp peak at about –50°F and it would appear more reasonable to expect that the critical locus curve extends below the critical temperature of methane. However, Fig. 15, 16, 17 were drawn so that the critical temperatures of methane and Kensol 16 bracketed the critical temperatures of mixtures.

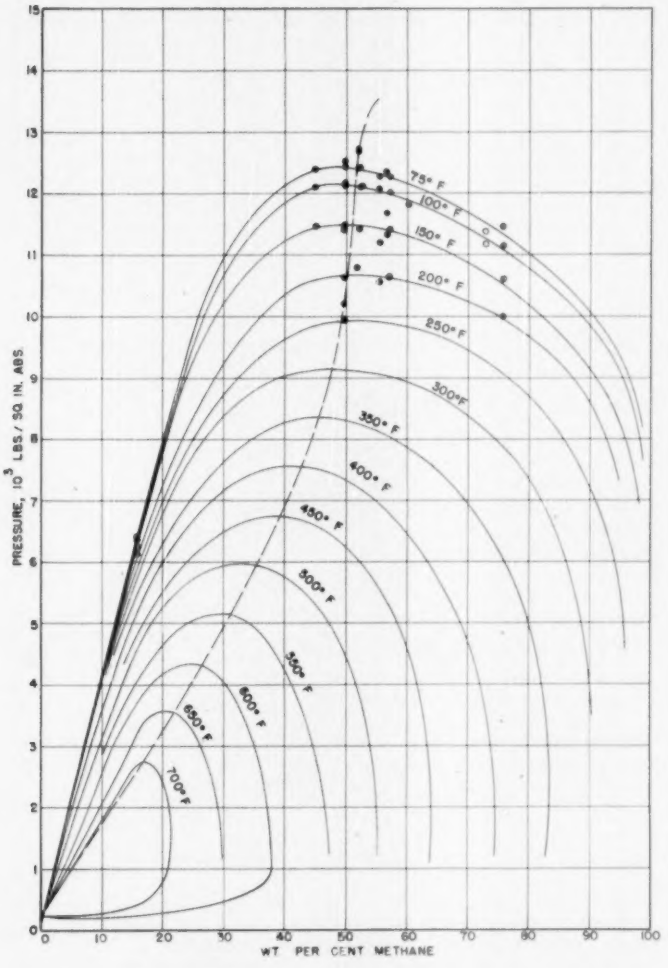

FIG. 16 — PRESSURE-COMPOSITION DIAGRAM OF METHANE-KENSOL 16 SYSTEM

Vapor-Liquid Equilibria

One of the most convenient tools in estimating the physical reactions of hydrocarbon systems to varying conditions of pressure and temperature is the equilibrium vaporization factor or "constant" as it is frequently called. It is used in the computations of bubble and dew points, the relative amounts of liquid and vapor phases and the compositions of the coexistent phases, under varying pressures and temperatures. The equilibrium vaporization factor was first proposed by Souders, Selheimer and Brown[18] and is defined as

$$K = y/x$$

where

K = equilibrium vaporization factor at equilibrium pressure and temperature,
y = mol fraction of component in vapor phase,
x = mol fraction of component in liquid phase.

Fig. 15, 16, 17 provide the means for computing the equilibrium vaporization factors for methane and Kensol 16. Table I gives the computed values of these factors. The equilibrium factors for methane are plotted in Fig. 19 as a function of temperature with lines of constant pressure, with a similar plot for Kensol 16 in Fig. 20.

A more convenient and clear method of presenting equilibrium factors is to plot the conventional log K versus log P charts with lines of constant temperatures, as has been done in Fig. 21 which shows isotherms of 0°F, 100°F, 400°F, and 600°F.

It is seen from Fig. 21 that the equilibrium vaporization factors converge to unity at different pressures for the different temperatures.

The pressures at which the factors converge to unity are called convergence pressures. It has been recognized that the convergence pressure is the critical pressure of the particular binary system which has its critical temperature at the temperature in question. For a binary system, therefore, the critical locus is the locus of the convergence pressures.

The equilibrium vaporization factor for a component in a binary system is fixed by specifying the temperature, pressure, and the particular binary system. It is also fixed by specifying the temperature, pressure, and convergence pressure at that temperature, in place of specifying the particular binary system.

Fig. 21 also shows how the factors for methane at 0°F cross the factors at 100°F and 400°F at successively lower pressures. This fact can also be seen from Fig. 19 which shows how the factors for methane rise at first with increase in temperature and then decrease to unity as the critical pressure, or convergence pressure, is reached.

In order to show the effect of convergence pressure on the equivalent vaporization factors for methane, Hanson, Rzasa and Brown[10] have presented a correlation based on binary paraffin systems, which was applied to the methane factors in the methane-Kensol 16 system. At all equilibrium pressures below about 4,000 lb psi absolute, the factors for methane are lower in the methane-Kensol 16 system than in the methane-decane system. Two possible explanations of this phenomenon may be advanced. First, the correlation presented by Hanson, Rzasa and Brown[10] applied to paraffin systems entirely, while in the present case the Kensol 16 is composed of only 64-66 per cent paraffins. Secondly, the peculiar shapes of the phase diagrams and critical locus of the methane-Kensol 16 system, with an extremely rapid shifting of the critical temperature with small changes in composition, may account for this decrease in the equilibrium factor. The same thing would be true if the factors for methane were correlated as a function of the molecular weight of the heavier constituent. The molecular weights of n-decane and Kensol 16

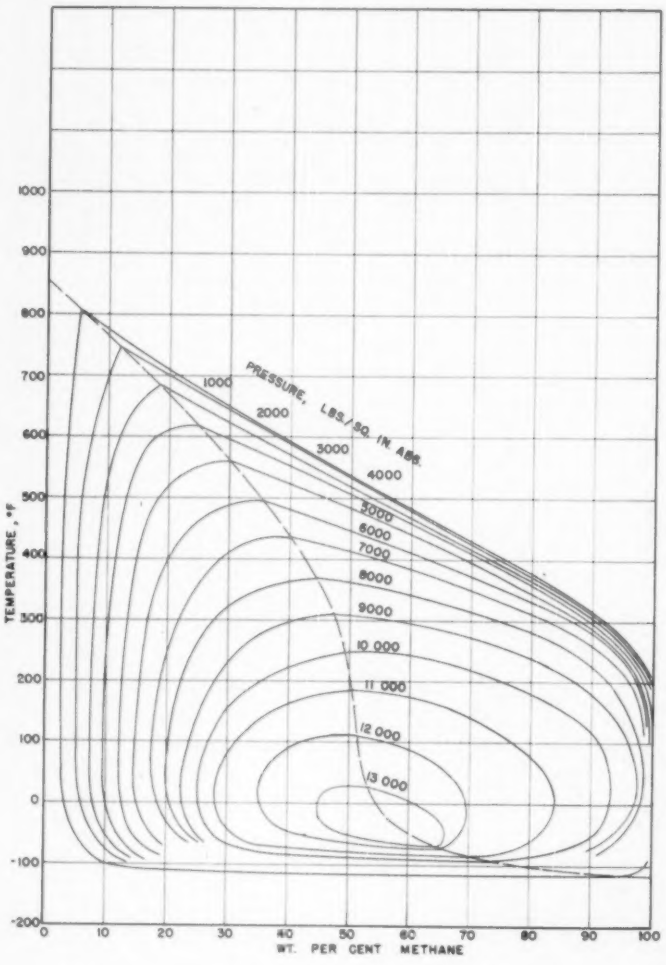

FIG. 17 — TEMPERATURE-COMPOSITION DIAGRAM OF METHANE-KENSOL 16 SYSTEM

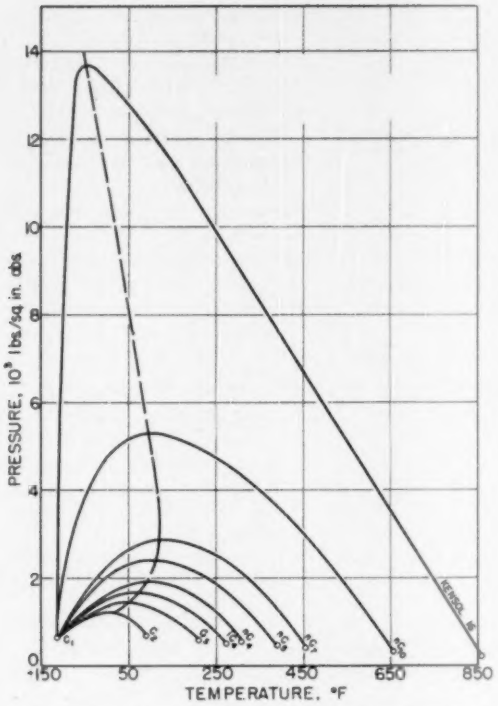

FIG. 18 — CRITICAL LOCI OF BINARY SYSTEMS CONTAINING METHANE

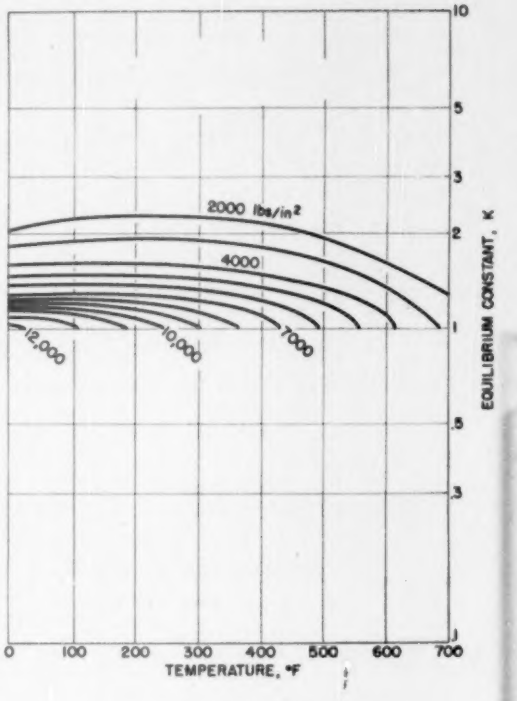

FIG. 19 — EQUILIBRIUM CONSTANTS FOR METHANE

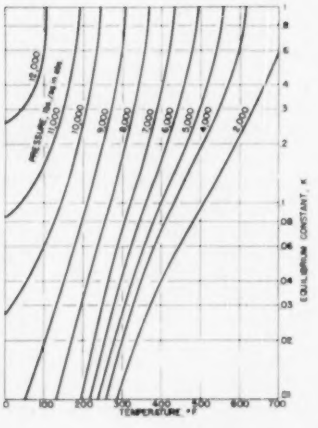

FIG. 20 — EQUILIBRIUM CONSTANTS FOR KENSOL 16

are 142.3 and 246.9, respectively, but the methane factors in the methane-Kensol 16 system are lower than they are in the methane-decane system. These observations are consistent with the results presented by Sage and Lacey.[24]

RELATIONS OF PRESENT WORK TO PETROLEUM PROBLEMS

Perhaps the most significant contribution of the present research to our knowledge of the physical reactions and phase behavior of petroleum fluids is the fact that two phases can coexist at pressures of 13,000 lb psi and above. As our search for oil continues, drilling depths will increase. Qualitatively, with increased depths we can expect to find oil pools with fluids containing more methane than that found in shallow wells. In that event, the control and production of these reservoirs may be complicated by the possible presence of two phases and operating techniques will be forced to take cognizance of that possibility. Heretofore it has been the general concensus that great well depths, of the order of 12,000 to 15,000 ft, would result in such high bottom hole pressures that the reservoir fluid would be expected to exist in the single phase. That this assumption may be invalid can be readily ascertained from the critical locus of the methane-Kensol 16 system.

Increase in drilling depths with consequent increase in bottom hole pressures will necessitate the study of phase relationships in the high pressure range, i.e., above 10,000 lb psi, and the present results are a step in that direction.

CONCLUSIONS

The following have been accomplished:

1. Phase diagrams for six mixtures of methane and Kensol 16 were ex-

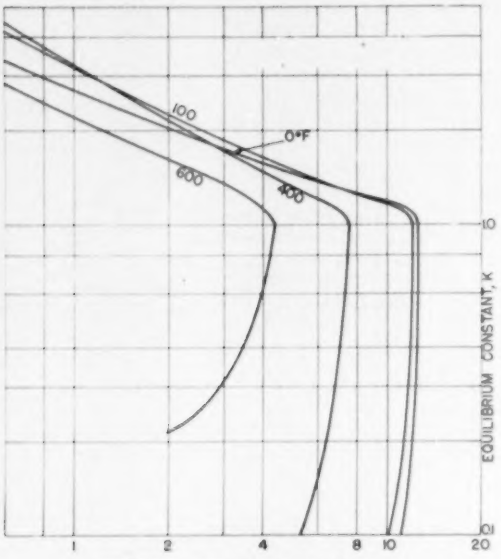

FIG. 21 — EQUILIBRIUM CONSTANTS

perimentally determined to pressures above 13,000 lb psi.

2. The coexistence of liquid and vapor phases above 10,000 lb psi was demonstrated.

3. The critical points of three methane-Kensol 16 mixtures were determined as follows:

Composition	T_c, °F	P_c, psia	ρ_c, gm/cc
49.80 wt. % methane	235	10,200	0.458
52.00 wt. % methane	55	12,670	
52.10 wt. % methane	51	12,700	0.545

4. A critical locus of the methane-Kensol 16 system was prepared from the experimental data.

5. The equilibrium vaporization factors for methane and Kensol 16 were estimated from the experimental data and extrapolated to 700°F.

6. The conclusion was reached that, for binary systems the influence of wide differences in volatility is such that the maximum pressure on the critical locus is shifted toward the compound of highest volatility, with the shift becoming more pronounced as the volatility spread increases.

7. For mixtures of wide-spread volatility it is very difficult, if not impossible, to determine the saturation pressures by the conventional pressure-volume curves, even at conditions well removed from the critical point. Visual means appear to be the most reliable method of determining these transition points.

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JUNE

8	Illinois Basin Chapter
12	Mid-Continent Section
15	South Plains Sub-Section
26	Pacific Petroleum Chapter
26-30	ASTM 53rd annual meeting and 9th exhibit of testing apparatus and equipment, Atlantic City, New Jersey

JULY

20	South Plains Sub-Section
24	Pacific Petroleum Chapter

AUGUST

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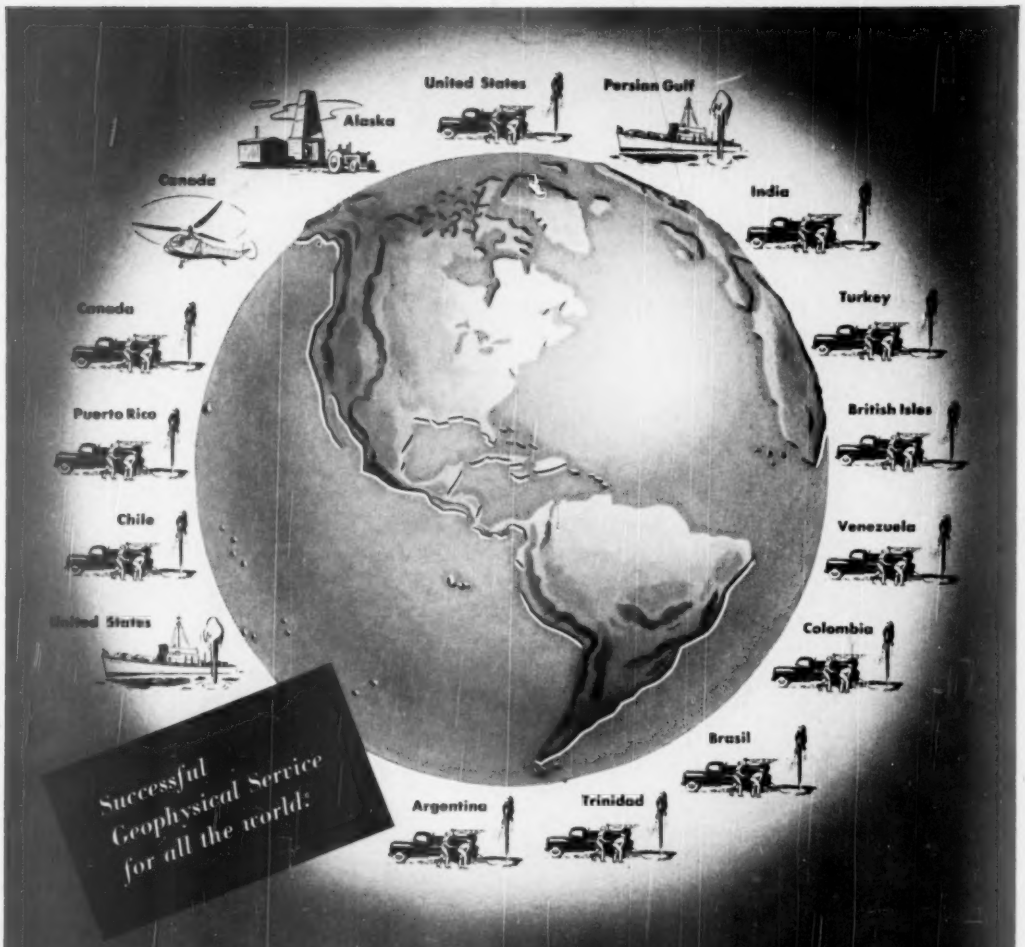

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